Том 4 № 4 (2018)

ISSN 2413-9203

ТРАНСПОРТНЫЕ СИСТЕМЫ И ТЕХНОЛОГИИ

рецензируемый научный журнал

TRANSPORTATION SYSTEMS AND TECHNOLOGY

peer-review journal

VOL. 4 ISSUE 4 (2018)

transsyst.ru

ЭЛЕКТРОННЫЙ РЕЦЕНЗИРУЕМЫЙ НАУЧНЫЙ ЖУРНАЛ ISSN 2413-9203

ТРАНСПОРТНЫЕ СИСТЕМЫ И ТЕХНОЛОГИИ

Том 4, № 4 2018

ЭЛЕКТРОННЫЙ РЕЦЕНЗИРУЕМЫЙ НАУЧНЫЙ ЖУРНАЛ

УЧРЕДИТЕЛЬ И ИЗДАТЕЛЬ
Федеральное государственное бюджетное образовательное учреждение высшего образования «Петербургский государственный университет путей сообщения Императора Александра I» (ФГБОУ ВО ПГУПС)

«ТРАНСПОРТНЫЕ СИСТЕМЫ И ТЕХНОЛОГИИ»
Электронный рецензируемый научный журнал
Выходит ежеквартально – 4 раза в год
Основан в 2013 году

ИНДЕКСАЦИЯ
РИНЦ (Российский индекс научного цитирования)
Google Scholar
WorldCat
Ulrich's Periodical Directory

КОНТАКТЫ
Адрес: 190031, Санкт-Петербург, наб. реки Фонтанки, 115, ауд. 9/11-5
E-mail: info@transsyst.ru
WEB: www.transsyst.ru
Телефон: +7 (812) 6198152; +7 (911) 2384445

Научный редактор Ю. Ф. Антонов, доктор технических наук, профессор
Перевод на английский язык А. Ю. Гнатенко
Выпускающий редактор Т. С. Антонова
Редактор сайта А. В. Дитрихс
Литературный редактор Е. В. Васильева
Верстка А. А. Стуканова

СВИДЕТЕЛЬСТВО о регистрации средства массовой информации
ЭлNºФС77-53673 от 17.04.2013 г. выдано Федеральной службой по надзору в сфере связи, информационных технологий и массовых коммуникаций

ОПИСАНИЕ ЖУРНАЛА
Сетевой электронный журнал "Транспортные системы и технологии" публикует статьи фундаментального характера и прикладного направления, а также обзорные статьи, относящиеся ко всем видам транспортной технологии

ПУБЛИКАЦИЯ В ЖУРНАЛЕ
Журнал отбирает материал для публикации из числа присланных для рассмотрения рукописей. В ходе отбора проводится независимое двойное слепое рецензирование членами редакционной коллегии и внешними экспертами. Для публикации рукопись, а также все сопроводительные и дополнительные файлы следует направить в редакцию через личный кабинет на сайте журнала по URL: http://trassyst.ru/
Рукопись и дополнительные материалы следует оформить в соответствии с правилами редакции, см. подробно по https://transsyst.ru/transsyst/about/submissions

ПОДПИСКА
Журнал распространяется через Интернет без ограничений и по адресно-целевой подписке через редакцию

FOUNDER AND PUBLISHER
Emperor Alexander I St. Petersburg State Transport University
St. Petersburg, Russia

"TRANSPORTATION SYSTEMS AND TECHNOLOGY"
Electronic peer-reviewed research journal
Issued 4 times a year (quarterly)
Established in 2013

INDEXING
eLibrary (Russian Science Citation Index)
Google Scholar
WorldCat
Ulrich's Periodical Directory

CONTACTS
Address: 190031, St. Petersburg, 115 Moskovskiy Ave., room 9/11-5
E-mail: info@transsyst.ru
Website: www.transsyst.ru
Phone: +7 (812) 6198152; +7 (911) 2384445

Science Editor Yu. F. Antonov, Doctor of Technical Science, Professor
Translation into English A. Yu. Gnatenko
The Executive Editor T. S. Antonova
WEB- Editor A. V. Dietrichs
Literary Editor E. V. Vasileva
Layout Editor A. A.Stukanova

AIMS & SCOPE

Network electronic journal "Transportation Systems and Technology" publishes articles of a fundamental nature and application areas, as well as review articles pertaining to all types of transport technology

JOURNAL CONTENT SELECTION

The journal selects material based on the double-blind peer-review conducted by members of the editorial board and external experts.

To be published, the manuscript and all accompanying files should be sent to the editorial team through a personal account on the journal's website at: http://trassyst.ru/

The manuscript and additional materials should be prepared and arranged in accordance with the author guidelines (see in detail at: https://transsyst.ru/transsyst/about/submissions

SUBSCRIPTION

The Journal is distributed via Internet for free and by subscription via Editorial office

TRANSPORTATION SYSTEMS AND TECHNOLOGY

Vol. 4, Issue 4 2018

ELECTRONIC PEER-REVIEWED RESEARCH JOURNAL

СОДЕРЖАНИЕ		TABLE OF CONTENTS
ОБЗОРЫ		**REVIEWS**

DOI 10.17816/transsyst2018445-31

© **M. Janić**
Delft University of Technology
(Delft, Netherlands)

MULTICRITERIA EVALUATION OF THE HIGH SPEED RAIL, TRANSRAPID MAGLEV AND HYPERLOOP SYSTEMS

This paper presents the multicriteria evaluation of the High Speed Rail (HSR), TransRapid Maglev (TRM) and Hyperloop (HL) passenger transport system assumed to operate as the mutually exclusive alternatives along the given line/corridor. For such a purpose the methodology is synthesized consisting of the analytical models of indicators of performances of these systems used as the evaluation criteria and the multicriteria Simple Additive Weighting (SAW) method. Given the characteristics of infrastructure and rolling stock/fleet of vehicles/trains reflecting the systems' infrastructural and technical/technological performances, the indicators of operational, economic, environmental, and social performances are defined and modelled respecting the interests and preferences of the particular actors/stakeholders involved. These are users/passengers, the systems' transport operators, local, regional, and national authorities and investors, and community members.

The proposed methodology is applied to the line/corridor Moscow – St. Petersburg (Russia) by assuming that three HS systems exclusively operate there according to "what-if' scenario approach. The results indicate that, under given conditions, the HL is the preferable compared to the TRM and HSR alternative.

Keywords: High Speed Rail (HSR), Trans Rapid Maglev (TRM), Hyperloop (HL), multicriteria evaluation, methodology, indicators of performances, criteria

1. INTRODUCTION

Increasing of transport speed has been an endeavour for people for a long time. In general, due to the limitations on time and monetary budget in combination with permanent intention to maximise travel distances (i.e., territory), the high-speed at lower as possible costs have become crucial requests and later the main goal in developing innovative and new transport systems. Consequently the HS transport systems have been emerging. The already fully operational are High Speed Rail (HSR) and Air Passenger Transport (APT) [1]. In addition, the operational (China), under construction (Japan), and under consideration in many other countries, the forthcoming TransRapid Maglev (TRM), and particularly the most recent (still at the conceptual stage) Hyperloop (HL) system have joined the former two, the latest certainly as the completely new HS transport system.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

In general, the HS transport systems have been compared and evaluated by different approaches. Most of them have included listing and quantifying the internal and external performances and their comparisons in the absolute terms. Under such circumstances, the outcome has always indicated strength of one over the other considered systems with respect to the one and weakness respecting the other set of performances [2]. In addition, the potential investors, policy makers, political leaders, and the public have been presented the new systems by citing not only innovative but also other performances not unique to them, very often in the rather "promotional" way. More professional review of these unique performances carried out latter on has very often indicated that the promoted "advantages" of the new system(s) were actually not unique. Therefore, a rational comparison of the new systems compared to the existing ones based on a systematic evaluation of their major performances has had to be carried out. One of the approaches, in addition to the frequently used Cost-Benefit Analysis (CBA), has been application of the different multicriteria evaluation methods/techniques. These have enabled comparison of these systems as "packages" based on the selected indicators of their performances used as evaluation criteria [3, 4].

This paper deals with multicriteria evaluation of the HSR, TRM, and HL system serving users/passengers as the mutually exclusive alternatives along the given line/corridor. In some sense, this represents a continuation of the author's previous work on the multicriteria evaluation of the HS systems including HSR, TRM, and APT [3]. In addition to this introductory section, the paper consists of four other sections. Section 2 describes the main developments of particular HS systems. Section 3 describes the multicriteria evaluation methodology. This consists of the analytical models of indicators of the selected performances to be used as evaluation criteria, and the entropy method for estimating the relative importance, i.e., "weights" of particular criteria, and the SAW (Simple Additive Weighting) multicriteria method. Section 4 presents an application of the proposed methodology to the selected HS line/corridor between Moscow and St. Petersburg (Russia) in which three systems are assumed to operate as mutually exclusive alternatives according to "what-if' scenario approach. The last section comprises some main conclusions.

2. DEVELOPMENTS OF THE HIGH SPEED (HS) TRANSPORT SYSTEMS

2.1. The High Speed Rail system

The High Speed Rail (HSR) systems have been developing worldwide (Europe, Far East-Asia, and USA as the rather innovative HS transport systems

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

within the railway-based transport mode. Despite the common name, different definitions of these systems have been used in the particular world's regions. In Japan, the HSR system is called "Shinkansen" (i.e., 'new trunk line') at which trains can operate at the speeds of at least and above 200 km/hr. The "Shinkansen" system's network has been built with the specific technical standards (i.e., dedicated tracks without the level crossings and the standardized and special loading gauge). In Europe the HSR system including compatibility of infrastructure and rolling stock enables operating speeds equal or greater than 250 km/h (Category I). In China, according to Order No. 34, 2013 from the China's Ministry of Railways, the HSR system (Its specific acronym is – China Railway High (CRH)) refers to the newly built passenger dedicated lines with (actual or reserved) speed equal and/or greater than 250 km/h. In the USA, the HSR system is defined as that providing the frequent express services between the major population centers on the distances from 321.8 to 965.4 km with a few intermediate stops, at the speeds of at least 241.35 km/h). This to be carried out on the completely grade-separated, dedicated rights-of-way lines [5–7] of the cross-section of the HSR line.

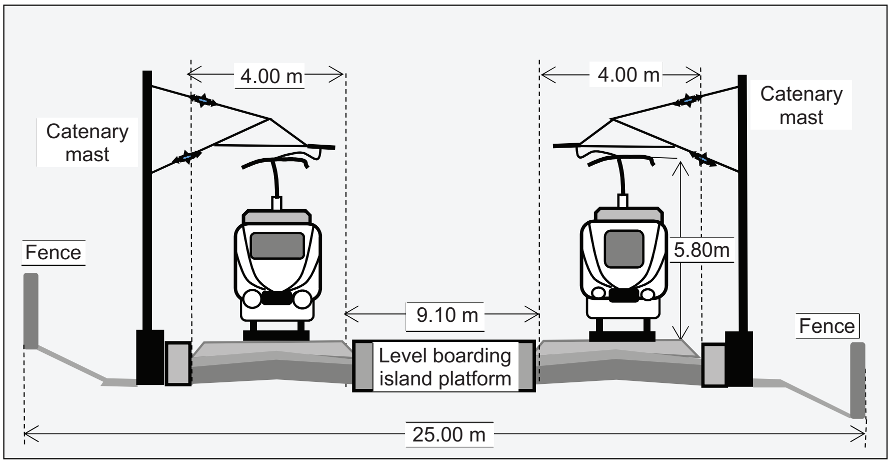


Fig. 1. Scheme of the right-of-way of the HSR systems [8]

2.2. The TransRapid Maglev system

The TransRapid MAGLEV (TRM) as the High Speed (HS) system is based on the Herman Kemper's idea of magnetic levitation dated from 1930s. The magnetic levitation enables suspension, guidance, and propelling the TRM vehicles by magnets rather than by the mechanical wheels, axles, and bearings as its HSR wheel/rail counterpart. Two forces - lift and thrust or propulsion - both created by magnets are needed for operating the TRM vehicle. Although TRM system has been matured to the level of commercialization, its infrastructure has only been

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

fragmentary built, mainly connecting the airport (s) with the city centers, which is still far from development of the network similarly as that of the High Speed Rail (HSR) [1, 9, 10]. Table 1 gives some time milestones of developing the TRM system.

Table 1. The time milestones of developing TransRapid MAGLEV system [1, 11]

1970s	The research on the Maglev transportation had been intensified (Japan, Germany).
1977	The first TRM (TransRapid Maglev) test line of the length of 7 km had been built (the test speed achieved was: 517 km/h) (Japan).
1993	The TRM test of 1674 km had been carried out (the achieved speed was: 450 km/h) (Germany).
1990/ 1997	The Yamanashi TRM test line of the length of 42.8 km had been constructed in the year 1990 and the first test carried out in the year 1997 (EDS - Electro Dynamic Suspension) (Japan).
2004	The first TRM line between Shanghai and its Pudong International airport (China) was built and commercialized (Length of line: 30 km; Average travel time: 7.33 min; Average speed: 246 km/h; Transport service frequency: 4 dep/h.

In addition, Fig. 2 shows the simplified scheme of the right-of-way of the TRM line.

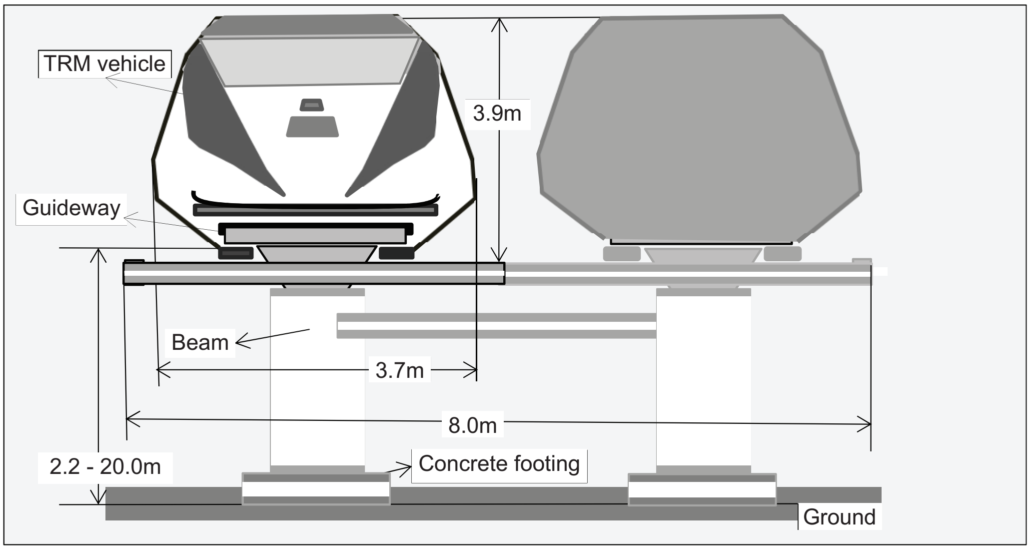


Fig. 2. Scheme of the right-of-way of the TRM system [1]

2.3. The Hyperloop system

The Hyperloop (HL) is the newest HS transport system currently in the conceptual stage. It is claimed to be with the superior operational, economic,

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

environmental, and social performances particularly compared to those of HSR system [12, 13]. However, these are still to be eventually confirmed after an initial commercialization of the system. The main components of HL system are:

a) Infrastructure;

b) Rolling stock/capsules;

c) Supporting facilities and equipment.

a) Infrastructure

The main infrastructure of the HL system includes the vacuumed tubes with the stations along them enabling operations of the HL rolling stock/vehicles/capsules. The tubes are the steel-made with the wall thickness of 20 and 30 mm and the diameter of 2.23 m for the version "Hyperloop Passenger Capsule" and 3.6 m for the version "Hyperloop Passenger Plus Vehicle Capsule". They are positioned on the elevated pillars, which would be approximately at the distance for 30 m except for tunnel and bridge sections. The ultra-high vacuum of about 0.75 Torr) (0.015 psi or 100 Pa) (British and German standards; Torr = Toricheli) would be maintained in the tube (the standard aatmospheric pressure amounts 760 Torr or 1.013$10^5$ Pa). The scheme of the right-of-way of the "Hyperloop Passenger Capsule" version is shown on Fig. 3 [12, 13].

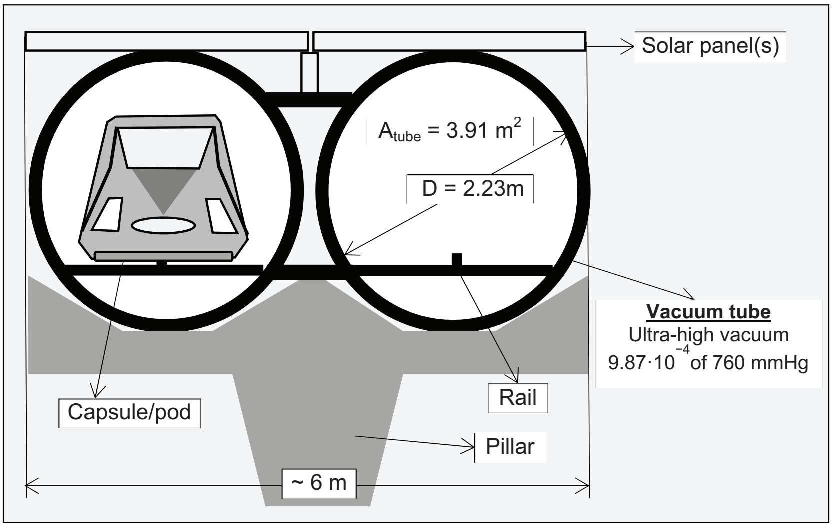


Fig. 3. Scheme of the right-of-way of the version "Hyperloop Passenger Capsule"

The stations of HL system would consist of three modules integrated within the tubes. The first is the chamber, which as a part of the vacuum tube handles the arriving HL capsule (ultimately the 'arriving' chamber). After entering the capsule, the chamber is de-vacuumed. Then, the capsule proceeds to the second module with the normal atmospheric pressure where passengers embark and/or disembark

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

it. After that, the capsule passes to the third chamber where at that moment the normal atmospheric pressure prevails (ultimately the 'departing' chamber). Then it spends time until the chamber is de-vacuumed, leaves it, and proceeds along the tube. This handling process of a capsule takes place at each station of the line.

The chambers are separated by the hermetic doors enabling establishing and maintaining the required air pressure in the above-described order [12].

b) Rolling stock/capsules

The rolling stock/capsules of the HL system operate within the above-mentioned vacuum tubes. Their size is adapted to the diameter of the tubes. Consequently, the frontal area of the version "Hyperloop Passenger Capsule" is 1.4 m^2 and that of the version "Hyperloop Passenger Plus Vehicle Capsule" is 4.0 m^2. They are supposed to "float" on a 0.5–1.3 mm layer of air featuring the pressurized air and the aerodynamic lift. Under such conditions, they will be able to operate at the maximum cruising speed of up to 1.220 km/h (the maximum acceleration is going to be higher than that of HSR, TRM, and commercial aircraft – about 1.5 m/s^2. The total (gross) weight of each capsule including its own, passenger, and luggage is planned to be 15 000 kg for "Passenger" and 26 000 kg for "Passenger Plus Vehicle" version, with the capacity of 28 seats/unit. The required aerodynamic power at the speed of 1 120 km/h is supposed to be about 285 kW with the drag force of 910 N (KW – Kilowatt; N – Newton). Fig. 4 shows the simplified scheme of the "Hyperloop Passenger Capsule" [12, 13].

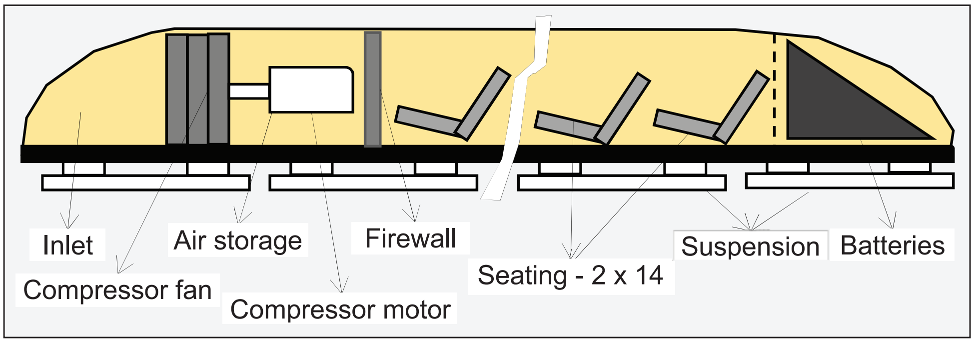


Fig. 4. Simplified scheme of "Hyperloop Passenger Capsule" [12]

c) Supporting facilities and equipment

The main supporting facilities and equipment are:

i) Power supply system;

ii) Vacuum;

iii) Vehicle and traffic control and management system. In addition, these are the maintenance systems for the previously mentioned components [12, 13].

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

i) Power supply system

The power supply system is based on the solar panels installed on the vacuum tubes, which collect the sun energy. This is then converted into the electric energy used by the supporting facilities and equipment and rolling stock/capsules [12].

ii) Vacuum pumps

The vacuum pumps are installed to initially evacuate and latter maintain the required level of vacuum inside the tubes and at the stations' first and third chambers. Creating vacuum within the tube implies an initially large-scale evacuation of air and later on removal of the smaller molecules near the tubes' walls using the heating techniques. These pumps would consume a rather substantive amount of energy. They would be located along the tube(s) in the required number depending on the volumes of air to be evacuated, available time, and their evacuation capacity. In addition, de-vacuuming and vacuuming chambers at the stations, the required number of vacuum pumps will operate accordingly [12, 13].

iii) Vehicle and traffic control/management system

This system within the tubes and at the stations mainly embraces switches, sidings, and airlocks. The switches will enable the vehicles to pass them at the maximum speed in all directions. With such switches, the vehicles with different destinations will not interfere with each other. The sidings located approximately at every 10 km along the tubes consist of the low speed switches and airlocks allowing evacuation of the users/passengers in cases of the serious technical failures. The airlocks are devices equipped with the gate valves allowing efficient boarding and disembarking of users/passengers inside the vacuum tube without the need to vent it entirely [12, 13].

3. A METHODOLOGY FOR MULTICRITERIA EVALUATION OF THE HS TRANSPORT SYSTEMS

3.1. Literature review

In the given context, it can be said that an enormous amount of the academic and consultancy research has been dealing with the HS transport systems. This can be divided into that analysing the systems themselves, their comparison, and the (multicriteria) evaluation. Some rather limited examples of analysing the systems themselves have included the HSR systems, which have also been often implicitly compared with Air Passenger Transport (APT) as the potential competitor on the short-to medium-long distances/routes [2, 5, 6, 7, 14]. The similar approach has been applied to analysing the TRM system [1, 15]. The concept of HL has been elaborated with mentioning its prospective advantages as compared to HSR and TRM system [12]. The illustrative cases of comparison of the particular HSR

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

systems have related to HSR and TRM [4, 9], as well as to HL and TRM [13]. An example of the multicriteria evaluation of the HSR, TRM, and APT has been the past author's work [12]. In certain sense, the present paper represents a continuation of the latest-mentioned author's work, but this time dealing with the multicriteria evaluation of three ground-based HS systems.

3.2. Objectives

The objectives of this paper are to synthesize a methodology for the multicriteria evaluation of three HS transport systems – HSR, TRM, and HL, serving users/passengers as the mutually exclusive alternatives along the given line/corridor. Consequently, the proposed methodology includes the multidimensional examination of their performances, development of the analytical models of indicators of performances for their quantification and use as the evaluation criteria, the entropy method for assessing their relative importance (i.e., weights) for the prospective DMs, and the Simple Additive Weighting (SAW) multicriteria evaluation method. Therefore, the main contributions of the research can be considering:

• Multidimensional examination of performances and development of the analytical models of their indicators respecting preferences of particular actors/stakeholders involved as the prospective DMs;

• Application of the proposed methodology to the real-life transport/corridor where three systems area assumed to exclusively operate according to "what-if" scenario approach.

3.3. The concept of performances

The considered performances of the above-mentioned three HS systems in the multicriteria evaluation are operational, economic, environmental, and social. They are dependent on the technical/technological characteristics of the systems' infrastructure and rolling stock/fleet of vehicles. The simplified scheme is shown on Fig. 5.

In general, the technical/technological characteristics of the HS systems' infrastructure relate to their lines, the stops along the lines, and the stations/terminals at their ends. Those of the rolling stock/fleet of vehicles relate to its/their type and space (seats and standings) capacity including the energy powering them. In addition, these are the characteristics of power supply and traffic control system, the latter including the traffic signalling system with components located along the HS lines and on board the rolling stock/fleet of vehicles. In addition:

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

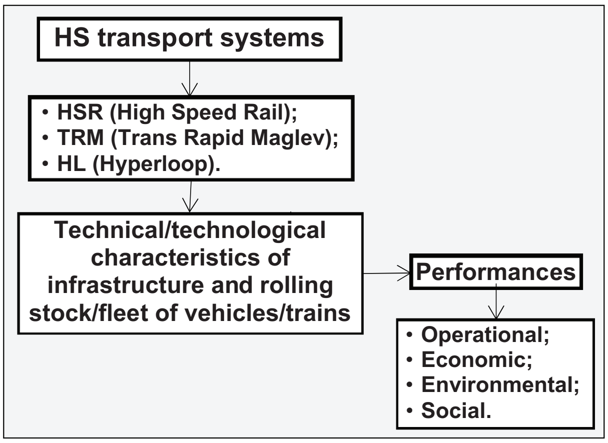


Fig. 5. Scheme of the considered performances of the HS systems

a) Operational performances are represented by the indicators such as:

i) Size of rolling stock/fleet of vehicles influenced by the volumes of user/passenger demand to be served, the required transport service frequency, and the turnaround time along the given HS line/corridors;

ii) Transport work;

iii) Technical productivity;

iv) Load factor of rolling stock/fleet of vehicles. As such, they are mostly relevant for transport operators, i.e., providers/suppliers of transport infrastructure and services.

b) Economic performances are represented by the indicators such as:

i) Operating costs[1] of a given HS system;

ii) Generalized travel costs of users/passengers;

iii) Welfare expressed by savings in the generalized travel costs of users/passengers if switching from the existing (lower speed) to one of three considered (higher speed) alternatives. They are mostly directly relevant for transport operators, i.e., providers/suppliers of transport infrastructure and services, users/passengers, and indirectly entire society.

[1] These generally include: i) Direct (train movement costs), ii) Commercial costs of customer services (non-direct costs), and iii) Other costs for the infrastructure use. The first embrace the costs of train ownership, rolling stock maintenance and cleaning, energy, operating personnel, and the marginal cost of infrastructure (covering its costs of investments and capital maintenance). The second includes the costs of distribution (sales) and access control, passenger services, advertising, general and structural, and working capital costs and bank and credit charges. The last include station and security charges and infrastructure charges above marginal costs [27].

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

c) Environmental performances are expressed by the indicators such as:

i) Energy/fuel consumption and corresponding emissions of Green House Gases (GHG);

ii) Land use;

iii) Waste (This latest is not particularly considered). They are mainly relevant for local communities, authorities at different levels, transport operators, and entire society.

d) Social performances are expressed by the following indicators:

i) Noise;

ii) Congestion;

iii) Traffic incidents/accidents (i.e., safety). They are mainly relevant for local communities, authorities at different levels, transport operators, and entire society.

At the environmental and social performances, the selected indicators express only direct impacts without considering their costs – externalities.

3.4. Modelling the indicators of performances

3.4.1. Assumptions

The models of above-mentioned indicators of performances of the three HS systems are based on the following assumptions:

• Each system operates along the given line/corridor as an exclusive HS alternative; this implies that competition between systems is not considered;

• Each system takes over the entire volumes of user/passenger demand, i.e., it is assumed to have 100 % market share;

• The volumes of user/passenger demand enable supply of transport service capacity up to the level of capacity of infrastructure – line and stations along it;

• The marginal contributions to GDP are equivalent to those of the current averages of the rail passenger transportation;

• Accessibility of all three systems from the corresponding urban areas is equivalent since their begin-end stations/terminals are assumed to be at the identical locations.

3.4.2. Operational performances

The main indicators of the operational performances are considered to be:

a) Required rolling stock/fleet of vehicles;

b) Transport work;

c) Technical productivity;

d) Load factor of the rolling stock/fleet of vehicles.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

a) Required rolling stock/fleet of vehicles

The size of rolling stock/fleet of vehicles is expressed by the number of trains of the given space capacity required to operate under conditions usually characterized by the transport service frequency carried out during a given period of time (h, day) and the trains' turnaround time along the given line/corridor. This required number of rolling stock/vehicles/trains can be estimated as follows [1, 16]:

$$RRS(\tau) = f(\tau) \times \tau_l, \tag{1a}$$

where $f(\tau)$ is the transport service frequency scheduled along the line/corridor during the time (τ) (dep/h or dep/day); τ is the time during which the transport services are scheduled (1h or 24h) (h – hour); and τ_l is the average turnaround time of a train along the line/corridor (min, h).

The transport service frequency $f(\tau)$ in Eq. 1a can be estimated as follows [8, 16]:

$$f(\tau) = \min\left[\mu_l(\tau); \mu_s(\tau); Q(\tau)/\left(\theta(\tau) \times \Delta S\right)\right], \tag{1b}$$

where $\mu_l(\tau)$ is the traffic capacity of the line/corridor (trains/h or trains/day); $\mu_s(\tau)$ is the traffic capacity of the stations/terminals along and both ends of the line/corridor (trains/h or trains/day); $Q(\tau)$ is the expected volumes of user/passenger demand on the line/corridor during the time (τ) (pax/h or pax/day per dir) (pax – passenger(s); dir – direction); $\theta(\tau)$ is the average load factor of the trains scheduled on the line/corridor during the time (τ) ($\theta(\tau) \leq 1.0$); S is the space capacity of a train (sp/vehicle/train) (sp – space: seats and standings).

Eq. 1b implies that all trains scheduled on the line/corridor are of the same space capacity. In addition, the transport service frequency cannot be higher than the traffic capacity of the line and the stations along it including begin and end station/terminal.

The average turnaround time of a train (τ_l) along the line/corridor in Eq. 1a is estimated as follows:

$$\tau_l = \tau_o + 2 \times \Delta\tau_l + \tau_d, \tag{1c}$$

where τ_o, τ_d is the average turnaround time of a train at the begin and end station of a line, respectively (min); $\Delta\tau_l$ the train's operating time along the line/corridor in single direction (min; h).

$$RRS(\tau) = f(\tau) \times \Delta\tau_l$$

In Eq. 1c, the train's turnaround time (τ_l) increases with increasing of the operating time along the line (the ratio between the length of line/route and the

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

operating speed), the number and duration of intermediate stops, all in both directions including those at the begin and end station/terminal, and vice versa.

The train's operating time along the line/corridor ($\Delta\tau_l$) in Eq. 1c can be estimated as follows:

$$\Delta\tau_l = \sum_{k=1}^{K-1}\left(\frac{l_k}{v_k} + \frac{v_k}{a_k}\right) + \sum_{k=1}^{K-2}\tau_{s/k} \text{ and } L = \sum_{k=1}^{K-1} l_k \ , \tag{1d}$$

where K is the number of intermediate stations along the line/corridor where the trains stop including the begin and end terminal; v_k is the operating speed of a train along the (k)-th interstation segment of the line (km/h); a_k is the average train's acceleration/deceleration rate along the (k)-th interstation segment of the line (m/s^2); $\tau_{s/k}$ is the time of a train stop at the (ki)-th intermediate station of the line/corridor (min); L is the length of line/corridor consisting of (K-1) segments between the intermediate stations (km); l_k is the length of the (k)-th interstation segment of the line/corridor (km).

b) Transport work

The transport work of the given line/corridor can be estimated for the supply and demand side. On the supply side, it counts the total offered number of spaces during a given period of time. On the demand side, it counts the total number of used spaces under the same conditions. Based on Eq. 1c, the transport work on a given line for the supply side and demand in terms of (s-km/h) (seat-kilometres per hour) and (p-km/h) (passenger-kilometres per hour), respectively, is estimated as follows [16]:

$$TW_1(\tau) = f(\tau)\times\Delta S\times\Delta L\ ;\ TW_2(\tau) = f(\tau)\times\Delta\theta\times\Delta S\times\Delta L\,, \tag{2}$$

where all symbols are analogous to those in the previous Eqs.

As can be seen, the transport work increases with increasing of the length of line, transport service frequency, the train's space capacity and load factor, and vice versa.

c) Technical productivity

The technical productivity of the given line/corridor at both supply and demand side expressed by the volumes of seat-km/h^2 and p-km/h^2, respectively, is estimated as follows [16]:

$$TP_1(\tau) = f(\tau)\times\Delta S\times\Delta\overline{v} \text{ and } TP_2(\tau) = f(\tau)\times\Delta S\times\Delta\theta\times\Delta\overline{v}\,, \tag{3}$$

where all symbols are analogous to those in the previous Eqs.

From Eq. 3, the technical productivity increases with increasing of the transport service frequency, the train space capacity, load factor, and the average operating speed, and vice versa.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

d) Load factor

The load factor reflects the utilisation of the capacity of rolling stock/fleet of vehicles serving the expected volumes of user/passenger demand during a given period of time. From Eq. 1b, the average load factor is as follows:

$$(\theta(\tau) = Q(\tau))/[f(\tau) \times \Delta S], \tag{4}$$

where all symbols are analogous to those in Equation 1b.

3.4.3. Economic performances

The indicators of economic performances are considered to be:

a) Operating costs;

b) Generalized user/passenger travel costs;

c) Users/passengers "welfare" in terms of savings in the generalized travel costs if switching from the existing (lower speed) to one of three considered (higher speed) alternatives;

d) Contribution to Gross Domestic Product (GDP).

a) Operating costs

The operating costs can be expressed by the total and the average amounts.

i) Total costs

The total costs of the given system infrastructure and transport services during the given period of time (i.e., usually 1 year) can be expressed as follows:

$$C = C_F + C_V, \tag{4a}$$

where C_F is the fixed cost of depreciation and capital maintenance, and administration of the given system's infrastructure and rolling stock/fleet of vehicles-trains during the given period of time (year) ($US or € per year); C_V is the operating costs of infrastructure (regular maintenance) and/or of the rolling stock/fleet of vehicles-trains (energy, maintenance, staff, infrastructure charges) during the given period of time ($US or € per year).

ii) Average costs

The average costs per unit of input ($US or €/space-km) and/or per unit of output ($US or €/ p-km), respectively, are equal to:

$$\overline{c}_i = \frac{C_T}{365 \cdot \tau \cdot f(\tau) \cdot S \cdot 2L} \quad \text{and} \quad \overline{c}_0 = \frac{C_T}{365 \cdot \tau \cdot f(\tau) \cdot \theta \cdot S \cdot 2L}, \tag{4b}$$

where all symbols are analogous to those in the previous Eqs.

Equation 4 (a, b) suggests that the average cost per unit of output decreases with increasing of the volume of its output during a given period of time.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

b) Generalized user/passenger costs

The generalized user/passenger cost along the given line/corridor can be estimated as follows:

$$cg(\tau) = \alpha \times \Delta\left[SD(\tau) + \Delta\tau_l\right] + P, \tag{5a}$$

where α is the average value of user/passenger time ($US or €/h-pax); $S_D(\tau)$ is the schedule delay (min; h); and *P* is the fare paid for a trip ($US or €/pax).

The other symbols are analogous to those in Eq. 1d.

The schedule delay (*SD*) in Eq. 5a is estimated based on an assumption that users/passengers arrive at the station/terminal at either side of the line/corridor uniformly distributed between any two successive train's departures during time (τ), as follows:

$$SD(\tau) = 1/2 \times \Delta\left[\tau / f(\tau)\right], \tag{5b}$$

where all symbols are as in the previous Eqs.

The fare (*P*) paid for a trip in Eq. 5a can be set up to cover the total operating costs and also provide some profits for transport operators.

c) Users/passengers "welfare"

The users/passengers "welfare" expressed in savings of their generalized travel costs thanks to switching from the existing lower to the new higher speed system introduced along the given line/corridor can be estimated as follows:

$$Scg_{i/j}(\tau) = Q_{i/j}(\tau) \times \Delta\{\beta_{i/j} \times \left[(SD_i + \Delta\tau_{l/i}) - (SD_j + \Delta\tau_{l/j})\right] + (P_i - P_j)\}, \tag{6}$$

where *i*, *j* is the existing lower speed and the new higher speed system, respectively; $Q_{i/j}$ is the volume of user/passenger demand switching from the existing lower speed system (*i*) to the new higher system (*j*) during time (τ) (pax/h, day, year); and $\beta_{i/j}$ is the average value of time of user/passenger switching from the existing system (*i*) to the new system (*j*) ($US or €/h-pax).

The other symbols are analogous to those in the previous Eqs.

d) Contribution to GDP

Contribution of each of three considered HS systems to the national GDP (Gross Domestic Product) is estimated as follows:

$$R_{GDP}(\tau) = \frac{s_{r/GDP} \cdot GDP(\tau)}{TTW_{r/2}(\tau)} \times TW_2(\tau), \tag{7}$$

where $s_{r/GDP}$ is the relative contribution of domestic rail passenger transportation to the national GDP (≤ 1.0); *GDP*(τ) is the national GDP during time (τ) ($US/year); $TTW_{r/2}(\tau)$ is the volume of domestic rail passenger transportation carried out

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

during time (τ) (p-km/year); $TW_2(\tau)$ is the volume of rail passenger transportation carried out by the particular HS systems along the given line/corridor during time (τ) (p-km/year);

3.4.4. Environmental performances

The indicators of environmental performances include the energy consumption and related emissions of GHG, and land use.

a) Energy consumption and emissions of GHG (Green House Gases)

The energy consumption and related emissions of GHG (Green House Gases) are considered exclusively from operations of vehicles/trains (HS and TRM trains, and the HL capsules) along the given corridor/line between its end stations/terminals without the intermediate stops. This implies exclusion of the energy consumed for building the infrastructure (lines), and manufacturing the supporting facilities and equipment and rolling stock (trains) [17].

The energy consumption of the above-mentioned trains/capsules generally includes that for acceleration, cruising, and deceleration. The energy is generally consumed for overcoming the rolling, aerodynamic, gradient and, at the TRM and HL (Hyperloop) system, levitation force. As well, the energy is consumed for powering the equipment on board the trains. In particular, during the acceleration phase of a trip the electric energy is converted into the kinetic energy at an amount proportional to the product of the train's mass and the square of its speed(s). A part of this energy recovers during deceleration phase by means by the regenerative breaking before the train's stop. During the cruising phase of a trip, the trains mainly consume energy to overcome the rolling/mechanical and the aerodynamic resistance. The TRM and HL use energy all the time for levitating. Under such conditions, the total energy consumed by a train operating along the given line/corridor of the length (L) in the single direction can be estimated as follows [18, 19]:

$$E_{TOT}(L) = (1/\eta) \times [E(l_a) + E(L - l_a - l_d) + E(l_d)], \qquad (7a)$$

where η is the efficiency of the given HS system's traction system ($\eta \le 1.0$); $E(l_a)$, $E(l_d)$ is the energy consumption during the train's acceleration and deceleration phase of the non-stop trip, respectively (J); $E(L–l_a–l_d)$ is the energy consumption during the train's cruising phase of non-stop trip (J); J is Joule (kgm^2/s^2).

The particular components of Eq. 7a are estimated as follows:

$$E(l_a) = 0.5 \times W_{TOT} \times v_a^2 + (1 - k_0) \times (1 - k_1) \times W_{TOT} \times g \times h + \\ + \begin{bmatrix} k_0 \times C_R \times W_{TOT} \times g + 0.5 \times C_L \times \rho \times A \times (v_a + w)^2 + \\ + k_1 \times W_{TOT} \times g \times sin\alpha_a \end{bmatrix} \times l_a \qquad (7b)$$

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

$$E(L-l_a-l_d)=(1-k_0)\times(1-k_1)\times W_{TOT}\times g\times h+ \\ +\begin{bmatrix} k_0\times C_R\times W_{TOT}\times g+\frac{1}{2}\times C_L\times\rho\times A\times(v_a+w)^2+ \\ +k_1\times Q_{TOT}\times g\times sin\alpha_c \end{bmatrix}\times \\ \times(L-l_a-l_d) \tag{7c}$$

$$E(l_d=0.5\times W_{TOT}\times(v_a-w)^2+(1-k_0)\times(1-k_1)\times W_{TOT}\times g\times h- \\ -\begin{bmatrix} k_0\times C_R\times Q_{TOT}\times g+0.5\times C_L\times\rho\times A\times(v_a-w)^2+ \\ +k_1\times W_{TOT}\times g\times sin\alpha_d \end{bmatrix}\times l_d, \tag{7d}$$

where W_{TOT} is the total mass of a vehicle/train (or HL capsule/pod) (kg); v_a, v_c, v_d is the speed of a vehicle/train (or HL capsule/pod) during acceleration, cruising, and deceleration, respectively (m/s); C_R, C_L is the coefficient of rolling and aerodynamic resistance, respectively; g is the gravitational constant (m/s^2); ρ is the air density (kg/m^3); A is the frontal area of a vehicle/train (m^2); α_a, α_c, α_d is the gradient angle of the guideway (or HL tube) segments where acceleration, cruising, and deceleration are performed, respectively (^{0}); L is the length of line (m); l_a, l_d is the acceleration and deceleration distance of a vehicle/train (m); w is the head wind (m/s); h is the height of levitation of a TRM train or HL capsule above the floor of the guideway or tube, respectively (m); k_0, k_1 is a binary variable taking the value “1” if a train/vehicle is levitating (i.e., TRM and/or HL) and the value “0”, otherwise.

From Eq. 7a, the energy consumed per non-stop trip expressed in (kWh/s-km) is equal to:

$$E(L)=[E_{TOT}(L)]\times 2.77778\times 10^{-7},$$

where 1 J = 2.77778×10^{-7} kWh.

From Eq. 7e, the emissions of GHG per trip along the given line/corridor in a single direction can be estimated as follows:

$$EM_{GHG}(L)=E(L)\times EMR, \tag{7e}$$

where EMR is the emission rate of GHG (gCO$_{2e}$/kWh).

b) Land use

The infrastructure of the HSR, TRM, and HL system occupies the area of land taken for the lines and stations/terminals. The largest proportion of land is generally taken for building the lines (ha) and can be approximately estimated as follows:

$$LU=L\times D, \tag{8}$$

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

where *D* is the width of cross-section of the line/corridor (m); *L* is the length of a line/corridor (m); *ha* is hectare (1ha = $10 \cdot 10^4$ m^2).

3.4.5. Social performances

The indicators of social performances generally reflect:

a) Noise;

b) Congestion;

c) Traffic incidents/accidents (safety).

a) Noise

The noise of the HSR, TRM, and HL system can be primarily generated from three physical sources:

1) rolling noise (mainly the rail and track base vibration – HSR;

2) traction noise – HSR;

3) aerodynamic noise – HSR, TRM;

4) impact noise (from crossings, switches and junctions – HSR;

5) noise due to additional effects such as bridges – HSR. This implies that HL is free of noise due to any causes thanks to operating in the vacuumed tube. The experienced noise mainly depends on its level generated by the source, i.e., passing by trains (in this case HS and TRM trains), and their distance from an exposed population/observer(s). Therefore, the noise depending on the distance between a passing by train and the potentially affected observer(s) can be estimated as follows [20]:

$$L_{AE}\left[r(t)\right] = L_{AE}(\gamma) - 20log_{10}\left[r(t)/\gamma\right], \quad (9a)$$

where *t* is the time of passing by trains at the distance ($r(t)$) and (γ)(min); $L_{AE}[r(t)]$, $L_{AE}(\gamma)$ is the noise from the source at the distances $r(t)$ and (γ), respectively (dBA); γ is the reference right-angle distance between the measurement location and passing by train (usually γ = 25m); $r(t)$, is the distance between passing by train and an observer ($\gamma \le r(t)$) (*m*).

b) Congestion

Thanks to the way of controlling successive trains operating simultaneously along the line/corridor, the HSR, TRM, and HL system are assumed to be free of congestion and consequent delays under regular operating conditions.

c) Traffic incidents/accidents (safety)

Similarly as at the road-based systems, the number of perceived incidents/accidents of particular train-based systems operating between the catchment area (CDB) and the airport serving it during a given period of time can be estimated as follows:

$$n_{ac}(\tau) = ac_r \times f(\tau) \times \theta \times S \times 2L, \quad (9b)$$

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

where ac_r is the train incident/accident rate (events, fatalities, injuries/p-km); $f(\tau)$ is the transport service frequency during time (τ). S is the space capacity (seats/spaces per departure); L is the length of line/corridor (km).

3.5. The Simple Additive Weighting (SAW) and the entropy method

The SAW multicriteria method is selected as the simplest and clearest method. It is often used as a benchmark for comparison of the results obtained from other discrete MCDMs (Multi Criteria Decision Making Method(s)) methods applied to the same problem. In general, the method requires the preselection of a discrete number of alternatives (three in this case) represented by the number of quantifiable (conflicting and non-commensurable) evaluation criteria of their performances. For the DM, particular criteria can reflect ‘costs’ and ‘benefits’. In such a case, a larger outcome means a stronger preference for the ‘benefit’ and less preference for the ‘cost’ criterion [21, 22].

The SAW method includes quantification of the values of indicators of performances and set up them as criteria for each alternative, construction of the Decision-Matrix ***A*** containing these values, derivation of the normalised decision-matrix ***R***, setting up the importance (weights) to criteria, and calculation of the overall score for each alternative. Then, the alternative with the highest score is selected as the preferable (best) one. The analytical structure of the SAW method for N alternatives and M attributes (criteria) is as follows:

$$S_i = \sum_{j=1}^{M} w_j \times r_{ij} \ \ for \ \ i = 1, 2, \ldots, N \ , \tag{10a}$$

where S_i is the overall score of the i-th alternative; r_{ij} is the normalised rating of the i-th alternative on the j-th criterion as an element of the normalised matrix ***R***; w_j is the relative importance, i.e., weight of the j-th criterion; N is the number of alternatives; M is the number of criteria.

The normalised rating of the i-th alternative on the j-th criterion can be computed as follows:

$$r_{ij} = x_{ij} / \left(\max_i x_{ij}\right), \text{ for the “benefit” criterion} \tag{10b}$$

and

$$r_{ij} = \left(1/x_{ij}\right) / \left[\max_i \left(1/x_{ij}\right)\right], \text{ for the “cost” criterion} \tag{10c}$$

where x_{ij} is an element of Decision-Matrix ***A***, which represents the “original” value of the j-th criterion of the i-th alternative.

The relative importance, i.e., weight of criteria in Eq. 10a can be estimated by the entropy method as follows [21]:

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst2018445-31

If (x_{ij}) is the the “original” value of the j-th criterion of the i-th alternative and an element of Decision-Matrix $\boldsymbol{A}$, the value (p_{ij}) can be determined as follows:

$$p_{ij} = x_{ij} / \sum_{i=1}^{N} x_{ij}, \quad for\ j \in M \tag{10d}$$

Then, the entropy of the criterion (j), (E_j) for (N) alternatives can be expressed as follows:

$$E_j = \left[-1/ln(N)\right] \times \sum_{i=1}^{N} p_{ij} ln\left(p_{ij}\right), \quad for\ j \in M \tag{10e}$$

where the term [–1/ln(N)] provides fulfilment of the condition $0 \leq E_j \leq 1$.

If the Decision-Maker (DM) does not have a reason to prefer one criterion to the others, the weight of the criterion (j) in Eq. 10a, (w_j) can be determined as follows:

$$w_j = \left(1 - E_j\right) / \sum_{j=1}^{M} \left(1 - E_j\right) \tag{10f}$$

4. APPLICATION OF THE PROPOSED METHODOLOGY

4.1. Description of the case

The proposed methodology is applied to the line/corridor between Moscow and Sank Petersburg (Russia). Currently, the corridor is served by the Sapsan HSR services operating at the maximum speed of: v = 250 km/h, taking an average of: $\Delta\tau_l$ = 3.75 h to cover the distance of: L = 650 km. The transport service frequency is: $f(\tau)$ = 1 dep/h (τ = 1 h), which gives the schedule delay of: SD = ½ (60/1) = 30 min = 0.5 h. The average fare per trip is: P = 89 $US/pax-trip [23]. This HSR system is planned to be replaced by the exclusively built new HSR line of the length of: L = 660 km enabling operations of the HS trains at the maximum speed of v = 350 km/h. The same length would be of the alternative HS systems – TRM and HL, if considered. Accessibility of three systems from the corresponding urban areas would be the same since the begin-end stations/terminals would be located at the current rail stations (Moscow: Moscow Leningradsky also known as Moscow Passazhirskaya station, and St. Petersburg: St. Petersburg-Glavny rail station) [23]. The estimated volumes of users/passenger demand to be served in the given corridor exclusively by either system in the year 2030 would be: $Q = 12.8\times10^6$ pax/yr, or $q = (12.8/2)\times10^6/365 \approx 17534$ pax/day. These volumes implicitly imply the self-generated and attracted user/passenger demand, the later from the other transport modes – current HSR Sapsan, road, and air [24]. The simplified scheme of the line/corridor is shown on Fig. 6.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

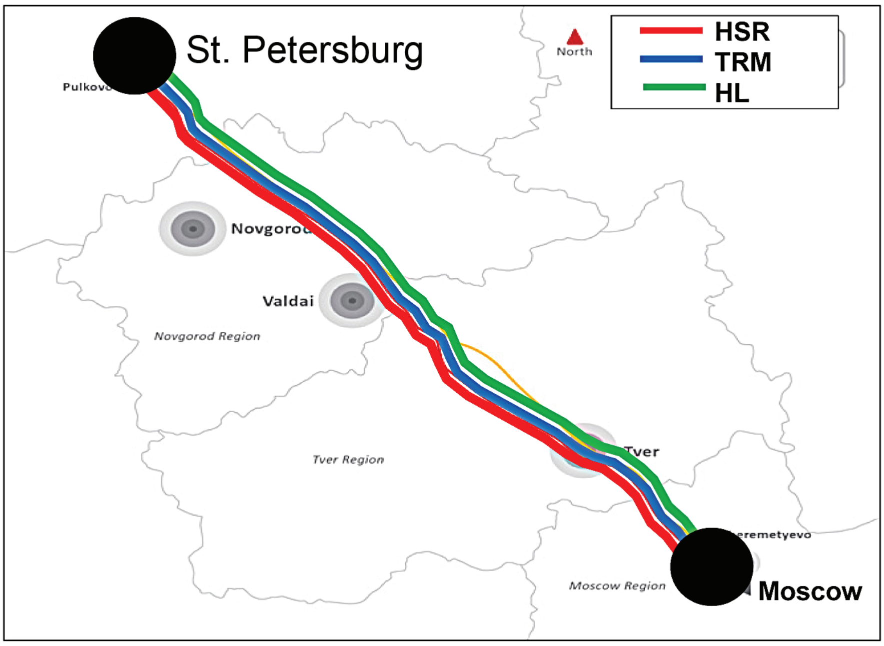


Fig. 6. Simplified scheme of the line/corridor Moscow-St. Petersburg (Russia) [24]

4.2. Input data

The inputs for estimating particular indicators of the operational, economic, environmental, and social performances influenced by the characteristics of infrastructure and rolling stock/fleet of vehicles/trains for three above-mentioned systems assumed to operate as the mutually exclusive alternatives along the given line/corridor connecting Moscow and St. Petersburg are given in Table 1. In

Table 1. Inputs on the characteristics of infrastructure and rolling stock/fleet of vehicles/trains: Line/corridor: Moscow - Sankt Petersburg

Input/System alternative	HSR	TRM	HL
Infrastructure			
Line/corridor - length (km) [24, 25]	660	660	660
Stations/terminals – number per line/corridor [24, 25]	2	2	2
Line traffic capacity (dep/h) [8]	30	20	20
Rolling stock/fleet of vehicles/trains			
Carriages per train	10 [26]	5[4)]	2[5)]
Gross weight (tons/train)	670	292	30
Propulsion (MW)	8.0 [26]	25 [15, 10]	21 [12]
Frontal area (m^2/train)	12.7	15.4	3.9
Capacity (seats/train-dep)	604	449	2·28
Avg. operating speed (km/h)	300	400	1000
Avg. acceleration/deceleration rate (m/s^2)	0.7	0.7	1.5

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

addition, the inputs for estimating indicators and the estimated indicators of the operational performances are given in Table 2.

Table 2. Inputs for estimating and the estimated indicators of operational performances: Line/ corridor: Moscow - Sankt Petersburg

Input/System alternative	HSR	TRM	HL
Inputs			
Demand (pax/day)[1)]	17534	17534	17534
Required service frequency (dep/day-dir)	32	54	360
Time of operation of transport services (h/day)	18	18	18
Required service frequency (dep/h-dir)	2	3	20
Travel time per direction (non-stop) (h)	2.23	1.69	0.71
Stop time at each end station/terminal (min)	15	15	15
Estimates			
Required rolling stock (vehicle units) [2)]	10	12	77
Transport work (p-km/h-dir)[3)]	717552	642761	643104
Technical productivity (p-km/h^2-dir)	358776	389552	940800
Load factor	0.90	0.72	0.87

[1)] Based on the estimated annual number of passengers per direction: Q = 12.8·106/2 = 6.4 ·10^6 pax/year the vehicle/train seating capacity (pax – passengers) [24]; [2)] For HL this is the number of capsules; for HS and TRM this is the number of train sets; [3)] p-km – passenger kilometer; h – hour; dir – direction

The inputs for estimating indicators and the estimated indicators of the economic performances are given in Table 3.

Table 3. Inputs for estimating and the estimated indicators of economic performances: Line/ corridor: Moscow – Sankt Petersburg

Input/System alternative	HSR	TRM	HL
Inputs			
Schedule delay (min)[1)]	15	10	1.5
Travel time per direction (non-stop) (h)	2.23	1.69	0.71
Avg. unit operating costs ($US/p-km) [12, 13, 27, 10]	0.173	0.120	0.086
Value of user/passenger time ($US/h) [28]	33.08	33.08	33.08
Avg. fare ($US/pax)[2)]	114	79	57
Contribution to GDP ($US/p-km) [29, 30]	0.00381	0.00381	0.00381
Estimates			
Operating costs (10^6 $US/year)	805.508	700.903	417.663
Generalized user's/passenger's costs ($US/trip)	196.04	140.42	81.31
User/passenger "welfare" (10^6 $US/year) [3)]	0.588	1.562	2.600
Contribution to GDP (10^6 $US/year) [4)]	36.590	32.179	32.196

[1)] Based on the transport service frequency; [2)] Based on covering the average operating costs (p-km – passenger kilometre; pax – passenger; h – hour); [3)] Savings in the generalized user/ passenger costs compared to the currently operating HS Sapsan trains [23]; [4)] Both directions.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

The inputs for estimating indicators and the estimated indicators of the environmental and social performances are given in Table 4.

Table 4. Inputs for estimating and the estimated indicators of environmental and social performances: Line/corridor: Moscow – Sankt Petersburg

Indicator /System alternative	**HSR**	**TRM**	**HL**
Inputs			
• <u>*Environmental*</u>			
Energy consumption (Wh//s-km) Emissions of GHG (gCO_2/s-km) [33, 34] Land use (width of right-of-way) (m) [9, 31, 12]	51 [31, 32] 487 25	52 [31, 32] 487 17	28.4[1)] 487 6 [12]
• <u>*Social*</u>			
Noise (dB (A)) [2)] Congestion (-) Traffic incidents/accidents (safety) (fatalities/pkm-year)	90.5 Free 0	88.5 Free 0	0 Free 0
Estimates			
• <u>*Environmental*</u>			
Energy consumption (10^3 kWh/day-dir) Emissions of GHG (tonCO_2/day-dir) Land use (ha)	650.558 316.836 1650	832.123 405.249 1122	377.480 183.833 396
• <u>*Social*</u>			
Noise (dB (A)) [2)] Congestion (-) [3)] Traffic incidents/accidents (safety) (fatalities/p-km-year)	90.5 0 0	88.5 0 0	0 0 0

[1)] Own calculations by Eq. 7 under assumption that HL would use electricity from the national electricity system and not from the solar panels due to prevailing weather/climate along the line/corridor (the energy consumed for vacuuming the tubes is not included) ; [2)] By trains passing at the right-angle distance of 25m at the speed of v = 300 km/h (HSR), and 400 km/h (TRM) [31]; [3)] Free of congestion

The estimated values of particular indicators of performances in Tables 2–4 are summarized in Table 5 as the final input for application of the above-mentioned SAW multicriteria evaluation method.

As can be seen, of the total 14 criteria, 5 have appeared as the "benefit" and the remaining 9 as the "cost" criteria.

4.3. Analysis of results

The results from application of the multicriteria evaluation methodology to the given case are given in Table 6.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

Table 5. Summary of the estimated indicators of performances of the three HS alternatives used as evaluation criteria in the given example: Line/ corridor: Moscow – Sankt Petersburg

Indicator/criteria	**Type (Orientation)**	**System/alternative**		
		HSR	**TRM**	**HL**
• ***Operational***				
Required rolling stock (vehicle units)	-	10	12	77
Transport work (p-km/h-dir)	+	717552	642761	643104
Technical productivity (p-m/h^2-dir)	+	358776	389552	940800
Load factor (-)	+	0.90	0.72	0.87
• ***Economic***				
Operating costs (10^6 US/year)	-	805.508	700.903	417.663
Generalized user/passenger costs ($US/ trip)	-	196.04	140.42	81.31
Users/passengers “welfare” (10^6 $US/ year)	+	0.588	1.562	2.600
Contribution to GDP (10^6 $US/year)	+	36.590	32.179	32.196
• ***Environmental***				
Energy consumption (10^3 kWh/day-dir)	-	650.558	832.123	377.480
Emissions of GHG (tonCO_2/day-dir)	-	316.836	405.249	183.833
Land use (ha)	-	1650	1122	396
• ***Social***				
Noise (dBA/passing by train)	-	90.5	88.5	0
Congestion (-)	-	0	0	0
Traffic incidents/ accidents (safety) (fatalities/p-km)	-	0	0	0

“-” ≡ “cost” criterion; “+” ≡ “benefit” criterion

As can be seen, according to the assumed “what-if” scenario, the most important criteria (with the highest weights) have been the ‘required rolling stock’, ‘noise’, and ‘users/passengers “welfare”’. The least important have appeared to be the ‘transport work’, ‘contribution to GDP’, and ‘load factor’. Due to the nature of operations and the lack of comparable data the criteria ‘congestion’ and ‘traffic incidents/accidents (safety), respectively, have not been weighted. As a result, overall the HL system has scored the highest followed by the TRM and HSR system. The latest has scored the lowest. However, the difference between the scores of TRM and HSR system has been marginal. The number of the highest nominal rates (r_{ij} = 1) has conditioned such score. It has been the highest for HL – 6 criteria (technical productivity, operating costs, generalized user/passenger costs, energy consumption and emissions of GHG and noise), and for HSR – 3 criteria (required rolling stock, transport work and contribution to GDP). The TRM system

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31
doi: 10.17816/transsyst2018445-31

Table 6. Results from application of the multicriteria evaluation methodology to the given case: Line/corridor: Moscow – Sankt Petersburg

Indicator/criterion (*j*)	**Weight of criterion (*j*) (w_j)**	**Normalized rates (r_{ij})**		
		System/alternative (*i*)		
		HSR	**TRM**	**HL**
• ***Operational***				
Required rolling stock (vehicle units)	0.302885	1.00000	0.83333	0.12987
Transport work (pax-km/h-dir)	0.001119	1.00000	0.89580	0.89600
Technical productivity (pax-km/h^2-dir)	0.076720	0.38100	0.41400	1.00000
Load factor (-)	0.003396	1.00000	0.80000	0.96700
• ***Economic***				
Operating costs (10^6 \$US/year)	0.028858	0.51851	0.59600	1.00000
Generalized user/passenger cost (\$US/trip)	0.042596	0.41500	0.57900	1.00000
Users/passengers “welfare” (10^6 \$US/year)	0.104771	0.26000	0.60000	1.00000
Contribution to GDP (10^6 \$US/year)	0.001598	1.00000	0.87940	0.87990
• ***Environmental***				
Energy consumption (10^3 kWh/day-dir)	0.034604	0.58000	0.45400	1.00000
Emissions of GHG (tonCO_2/day-dir)	0.034604	0.58000	0.45400	1.00000
Land use (ha)	0.095900	0.24000	0.35300	1.00000
• ***Social***				
Noise (dBA)/passing by train)	0.279916	0.01000	0.01130	1.00000
Congestion (-)	0	0	0	0
Traffic incidents/accidents (safety) (fatalities/pkm)	0	0	0	0
$\sum_{j=1}^{M} w_j$	1.00000			
$S_i = \sum_{j=1}^{M} w_j \cdot r_{ij}$		0.46052	0.46239	0.49041

has not have any nominal rate equal to one. Consequently, the main reasons for the HL system to score the best have seemed to be its overall lower operating costs, superior transport service frequency and operating speed benefiting to the user/passenger generalized travel costs, and a complete lack of the noise impact thanks to operating within the closed environment (tube). However, this score should be taken into account with caution. This is because estimation of the indicators of performances as criteria has been based just on the conceptual design of HL still not being operational anywhere. This implies a high uncertainty in the expected performances if the system would be implemented particularly in the given case.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):5-31

doi: 10.17816/transsyst2018445-31

The similar relates to the TRM system, which has been in the commercial use at the very limited scale (Shanghai Pudong International Airport connecting Longyang Road Station in the outskirts of central Pudong of the short route compared to the considered case – 30.5 km) [25]. Additional uncertainty not being included in the above-mentioned evaluation of both these systems is their robustness (i.e., resilience) to the impacts of different external and internal disruptive events (extreme weather, failures of components, and managing recoveries). Therefore, the most objective assessment of indicators of performances has been for the HSR operating at the very large scale worldwide including in the given case.

The additional question is about the 'credibility' of the proposed MCDM (Multi Criteria Decision Making) method for the DMs involved. The experience so far has shown that application of the other methods such as TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution), AHP (Analytic Hierarchy Process), DEA (Data Envelopment Analysis), and ELECTRE (ELimination Et Choix Traduisant la REalit´e – ELimination and Choice Expressing the REality) to the similar cases has produced the identical ranking scores. As well, application of the CBA method should not be neglected just for checking the overall financial feasibility of the considered alternatives as the support of the choice of the referable one. However, in any case, DMs should count on the rather "fuzziness" of inputs for estimating indicators of performances of the systems still at the very rough conceptual stage like the HL system is.

5. CONCLUSIONS

This paper has dealt with the multicriteria evaluation of the High Speed Rail (HSR), TransRapid Maglev (TRM) and Hyperloop (HL) passenger transport system assumed to operate as the mutually exclusive alternatives in the given line/corridor. For such a purpose, the methodology consisting of the analytical models of indicators of their performances used as criteria, the SAW (Simple Additive Weighting) method, and the entropy method for estimating the relative importance, i.e., weights, of particular criteria has been synthesized. The methodology has been applied to ranking the above-mentioned three HS systems assumed to operate as the mutually exclusive alternatives along the line/corridor Moscow – St. Petersburg (Russia). Given the characteristics of the infrastructure and rolling stock/fleet of vehicles, the fourteen indicators of the operational, economic, environmental, and social performances have been estimated based on a "what-if' scenario approach and then used as the evaluation criteria by the proposed Multi Criteria Decision making (MCDM) Method. The selected indicators of performances have aimed to reflect interests and preferences of particular DMs such could be direct systems'

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

users/passengers, transport operators, local, regional, and national authorities and investors, and community members.

The results have indicated that the HL system would perform as the preferable alternative under given conditions, followed by TRM and HSR system. Nevertheless, despite showing usefulness as a support to the Decision Making (DM) process, at least regarding the consistency of the approach, the proposed approach would need additional checking by using more reliable input data for quantification of particular indicators of performances, the strongest for the HL systems, which is still at the highly conceptual stage of elaboration. This raises the issues for the further research, which generally should contribute to the reliability of outcome(s) from MCDM evaluation. Therefore, the additional research could deal with the issues as follows:

• Consolidating additionally the quality of inputs for estimating indicators of performances, particularly for the HL and TRM system while operating along the long-haul lines/corridors;

• Widening the set of "what-if" operating scenarios by including those where the three HS systems would stop at the intermediate stops/stations and also compete with each other;

• Extending the set of indicators of performances by including more details – for example those related to resilience of three systems when being impacted by different external and internal disruptive events (if available);

• Evaluating the three HS systems by using other MCDM methods and the CBA as well; and last but not least

• Expanding the set of considered alternatives by including the fourth HS system – APT (Air Passenger Transport) – and then evaluating them under the above-mentioned conditions.

References

1. Janić M. Advanced Transport Systems: Analysis, Modelling, and Evaluation of Performances. UK: Springer-Verlag; 2014.
2. Feigenbaum B. High-Speed Rail in Europe and Asia: Lessons for the United States, Reason Foundation, Policy Study 418, USA: Los Angeles, CA; 2013.
3. Janić M. Multicriteria Evaluation of High-Speed Rail, Transrapid Maglev and Air Passenger Transport Systems in Europe. *Transportation Planning and Technology*. 2003;26(6):491-512. doi: 10.1080/0308106032000167373
4. Vuchic RV, Casello MJ. An Evaluation of Maglev Technology and Its Comparison with High Speed Rail. *Transportation Quarterly*. 2002;56(2):33-49
5. Campos J, de Rus G. Some Stylized Facts about High-Speed Rail: A Review of HSR Experiences around the World. *Transport Policy*. 2009;16:19-28. doi: 10.1016/j.tranpol.2009.02.008
6. EC. Interoperability of the Trans-European High Speed Rail System, Directive 96/48/EC, European Commission, Brussels, Belgium; 1996. p. 155
7. Janić M. A Multidimensional Examination of the Performances of HSR (High Speed Rail) Systems. *Journal of Modern Transportation*. 2016;21(1):1-24. doi: 10.1007/s40534-015-0094-y
8. Janić M. *Landside Accessibility of Airports*. Berlin: Springer; 2018.

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

9. Schach R, Naumann R. Comparison of High Speed Transportation Systems in Special Consideration of Investment Costs. *Transport*. 2007;22(3):139-147.
10. USDT. Costs and Benefits of Magnetic Levitation: Report to Congress, Federal Railroad Administration, U. S. Department of Transportation, Washington, D.C., USA, 2005.
11. Shanghai Maglev Train (SMT) [cited 2018 December 12]. Available at: https://www.travelchinaguide.com/cityguides/shanghai/getting-around.htm/.
12. Musk E. Hyperloop Alpha, Texas: SpaceX [cited 2018 December 12]. Available at**:** http://www.spacex.com/sites/spacex/files/hyperloop_alpha-20130812.pdf.
13. Taylor CT, Hyde DJ, Barr LC. Hyperloop Commercial Feasibility Analysis: High Level Overview, Volpe National Transportation research Centre, U.S. Department of Transportation, Cambridge MA, USA. 2016.
14. Wendell C, Vranich J. The California High Speed Rail Proposal: A Due Diligence Report, Reason Foundation. Los Angeles, California, USA (2008.
15. Cassat A, Bourquin V. MAGLEV – Worldwide Status and Technical Review. Proceedings of the Conference "Électrotechnique du Futur" 2011 Décembre 14–15; Belfort, France; 2011.
16. Vuchic RV. *Urban Transit Systems and Technology*. Wiley, New York, USA; 2007.
17. UIC. High Speed, Energy Consumption and Emissions. UIC Publications. International Union of Railways, Paris, France; 2010.
18. Jong JC, Chang FE. Models for Estimating Energy Consumption of Electric Trains. *Journal of the Eastern Asia Society for Transportation Studies*. 2005;6:278-291.
19. Rochard PB, Schmid F. A Review of Methods to Measure and Calculate Train Resistances. *Proceedings of the Institute of Mechanical Engineering Part F*. 2000;214:185-143. doi: 10.1243/0954409001531306
20. Teodorovic D, Janić M. *Transportation Engineering: Theory*, *Practice and Modelling.* Amsterdam: Elsevier; 2016.
21. Hwang LC, Yoon K. Multi Attribute Decision-Making: A Methods and Applications, Lecture Series in Economics and Mathematical Systems. Berlin: Springer-Verlag; 1981.
22. Zanakis SH, Solomon A, Wishart N, Dublish S. Multi-attribute Decision Making: A Simulation Comparison of Selected Methods. *European Journal of Operational Research*. 1998;107:507-529. doi: 10.1016/s0377-2217(97)00147-1
23. Sapsan high-speed train tickets [cited 2018 December 12]. Available at: https://www.russiantrain.com/sapsan?gclid/aAnNCEALw_wcB/.
24. RG (2011), "PPP Model to Fund Moscow-St. Petersburg High Speed Line", Railway Gazette, http://www.railwaygazette.com/news/single-view/view/ppp-model-to-fund-moscow-st-petersburg-high-speed-line.Html.
1. RR. High-Speed Trains", Russian Railways **[**cited 2017 June 3]. Available at**:** http://eng.rzd.ru/statice/public/rzdeng?STRUCTURE_ID=4054. 25.
26. Siemens AG. High Seed Trainset Velaro RUS for Russian Railways (RZD). Industry Sector, Mobility Division, Public Transit, Erlangen, Germany; 2012.
27. UIC. Relationship between Rail Service Operating Direct Costs and Speed. International union of Railways, Paris, France; 2010.
28. Wardman M, Chintakayala P, de Jong G, Ferrer D. European Wide Meta-analysis of Values of Travel Time. Final Report to the European Investment Bank. UK: University of Leeds; 2012.
29. RR. Annual Report 2016, Russian Railways, Moscow, Russia.
30. Russia: Gross domestic product (GDP) in current prices from 2012 to 2022 (in billion U.S. dollars) **[**cited 2017 June 3]. Available at**:** https://www.statista.com/statistics/263772/gross-domestic-product-gdp-in-russia/.
31. TKTA. ThyssenKrupp Transrapid Australia Submission in response to East West Link Needs Assessment report "Investing in Transport". ThyssenKrupp Transrapid Australia, ThyssenKrupp Transrapid Gmbh, Kassel, Germany; 2008.
32. UIC. High Speed Rail: Fast Track to Sustainable Mobility. *International Union of Railways*. Paris, France; 2010.
33. WNA. Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources, WNA Report World Nuclear Association, London, UK; 2011.
34. Global energy data at your fingertips [cited 2018 December 12]. Available at: http://www.iea.org/statistics/html/.
35. Shanghai maglev train [cited 2018 December 12]. Available at: https://en.wikipedia.org/wiki/Shanghai_maglev_train.

Milan Janić,
ORCID: 0000-0003-4917-467X
E-mail: m.janic@tudelft.nl

To cite this article:
Janić M. Multicriteria Evaluation of the High Speed Rail, Transrapid Maglev and Hyperloop Systems. *Transportation Systems and Technology.* 2018;4(4):5-31. doi: 10.17816/transsyst2018445-31

Received: 03.10.2018. Revised: 31.10.2018. Accepted: 17.12.2018.

UDC [УДК] 625.1/.5
DOI 10.17816/transsyst20184432-43

© P. A. Plekhanov, V. V. Shmatchenko
Emperor Alexander I St. Petersburg State Transport University
(St. Petersburg, Russia)

STANDARDISATION OF MAGLEV TRANSPORTATION SYSTEMS IN RUSSIA

Existing regulatory framework in Russia does not include a full set of rules and standards needed, as the main document is absent – Safety Regulations Governing Maglev Transportation Systems. However, in this case the Russian Legislation provides for development and application of a special document, namely Special Technical Conditions (STC). These technical safety requirements to a capital construction object, that include either supplementary technical conditions to those which have not been set yet or are lacking in terms of safety, as well as deviations for the set requirements. Using the international and national experience, the authors and their colleagues have designed nine STC for MLTS. These are "General Design Requirements", "Guideway", "Substructure, Artificial Structures, Junctions and Crossings", "Terminals, Intermediate Stations, Maintenance Facilities and Buildings", "Propulsion and Power Supply System", "Train Control System", "Communication Systems", "Vehicles", "Integrated Safety System". Also, as a result of the study, the English-Russian (Russian-English) MLTS Explanatory Dictionary was compiled.

Keywords: Standardisation, Maglev Transportation Systems, Regulatory Framework, Special Technical Conditions (STC).

© П. А. Плеханов, В. В. Шматченко
Петербургский государственный университет путей сообщения
Императора Александра I
(Санкт-Петербург, Россия)

СТАНДАРТИЗАЦИЯ МАГНИТОЛЕВИТАЦИОННЫХ ТРАНСПОРТНЫХ СИСТЕМ В РОССИИ

Сегодня в России нет полной нормативно-технической базы для создания магнитолевитационных транспортных систем (МЛТС), включая основной документ – Технический регламент о безопасности магнитолевитационного транспорта. Вместе с тем российским законодательством предусмотрена разработка и применение особого рода документов – специальных технических условий (СТУ). Это технические требования в

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43

doi: 10.17816/transsyst20184432-43

области безопасности объекта капитального строительства, содержащие дополнительные к установленным или недостающие технические требования по безопасности, а также отступления от установленных требований. Авторами и другими специалистами на основе мирового и отечественного опыта разработаны проекты девяти типовых СТУ для МЛТС: «Общие требования по проектированию», «Путь», «Основания для пути, искусственные сооружения, примыкания и пересечения», «Терминалы, промежуточные станции, служебно-технические здания и сооружения», «Система тяги и электроснабжения», «Система управления движением», «Система электросвязи и оповещения», «Подвижной состав», «Система комплексной безопасности». Кроме того, в результате проведенной работы подготовлен структурированный англо-русский (русско-английский) толковый словарь по МЛТС.

Ключевые слова: стандартизация, магнитолевитационные транспортные системы (МЛТС), нормативная база, специальные технические условия (СТУ).

INTRODUCTION

Magnetic Levitation Transport Systems (MLTS) is a further development of a conventional “wheel-rail” technology, the implementation of which requires development of respective regulatory framework for design, construction and operation. The MLTS related specific issues, namely traction, levitation, lateral stabilisation, power supply systems as well as overall safety, should receive special attention.

As of today, the world operates several passenger MLTS predominantly in the Eastern Asia states: Japan (Nagoya, Yamanashi), the Republic of Korea (Incheon), China (Shanghai, Changsha, Beijing). The realised MLTS projects are also present in the USA, Germany, and other states. The USSR conducted MLTS tests too.

In this regard, standardisation of MLTS in Russia should be carried out on the basis of the world experience and national practice of realisation of MLTS projects taking into account the active regulatory framework for design, construction and operation of transport systems.

RUSSIAN SYSTEM OF NORMATIVE AND TECHNICAL REGULATION FOR DESIGN, CONSTRUCTION AND OPERATION OF TRANSPORT SYSTEMS

The system of normative and technical regulation for design, construction and operation of transport systems in Russia encompasses normative legislative and normative technical documents (Fig. 1). At the same time, the structure and

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43

doi: 10.17816/transsyst20184432-43

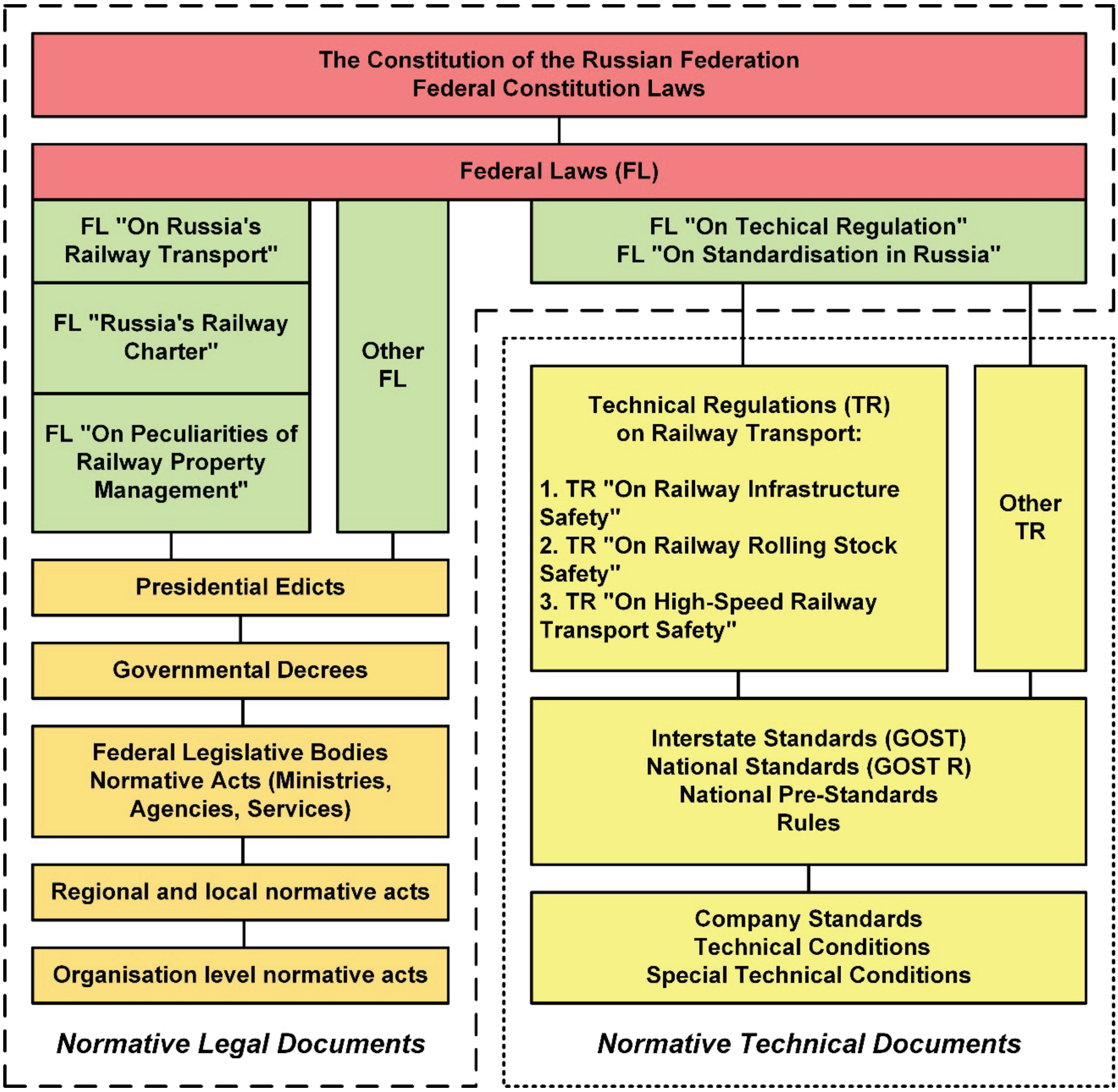


Fig. 1. The system of normative regulation for design, construction and operation of transport systems in Russia on the example of railway transport

composition of the Russian system of normative and technical regulation are determined by such normative legislative documents as Federal Laws "On Technical Regulation" and "On Standardisation in the Russian Federation" (Fig. 2).

At the upper sublevel of the state level of the system of normative technical regulation for safety the Technical Regulations (TR) are placed, which set mandatory requirements for product safety and life cycle processes. At the lower sublevel of the state level, there are Interstate Standards (GOST), National Standards (GOST-R), National Pre-Standards (PNST) as well as Norms and Rules (SP) voluntarily complied by to confirm meeting TR requirements.

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43

doi: 10.17816/transsyst20184432-43

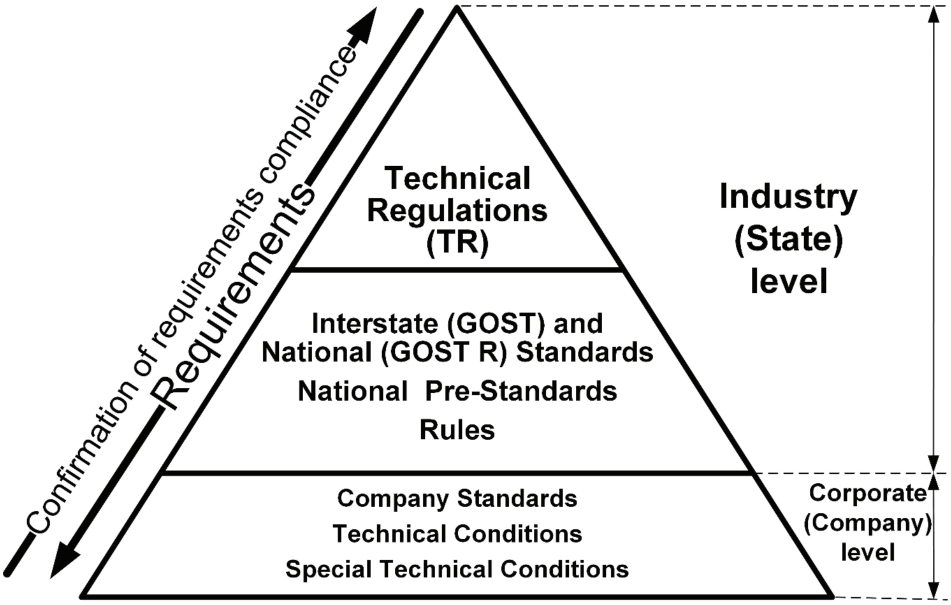


Fig. 2. The Russian system of normative technical regulation for safety

With the help of TR, the minimal required safety requirements are set, which qualitatively determine its necessary level. The quantitative indicators, which are used in manufacturing of production and certifying its life cycle processes compliance with these requirements, are contained in standards, and norms and rules, harmonised with the related TR. This approach enables making prompt corrections to qualitative characteristics in accordance with technical and technological changes, to ensure favourable conditions for innovations implementation. The standards as well as norms and rules met voluntarily are necessary to correctly understand and fulfill the mandatory requirements of the relative TR.

At a corporate level, it envisaged that various organisations should use their own normative technical documents: Company Standards (STO), Technical Conditions (TC), and Special Technical Conditions (STC) which will be covered further.

FORMATION OF REGULATORY FRAMEWORK FOR MAGLEV DEVELOPMENT

Today, Russia does not possess its own fully developed regulatory framework for design, construction, and operation of MLTS, which should comprise TR on maglev transport safety, GOST, GOST-R, PNST, and SP, containing requirements for subsystems and components of MLTS. However, some subsystems and components of MLTS come under separate TRs. These are, first of all, TRs such as “On Buildings and Structure Safety”, “On Machinery and Equipment Safety”,

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43

doi: 10.17816/transsyst20184432-43

"On Low-Voltage Equipment Safety", "Electromagnetic Compatibility of Technical Equipment", and others. Associated with these TRs are standards, norms and rules supporting them, which cover corresponding subsystems and components of maglev transport.

At the same time, with regards to construction of unique engineering structures Russia's legislation provides for development and application of STCs, which are technical requirements for capital construction object safety and which contain supplementary technical safety requirements to those which have not been set yet or are lacking. The order of design and approval of STCs are determined by Order of the Ministry of Transport № 248/pr of April 15th, 2016 "On Order of Design and Approval of Special Technical Conditions for Development of Project Documentation for Capital Construction Object", and "Guidelines "Order of Construction and Design of Special Technical Conditions for Development of Project Documentation for a capital construction object" (approved by Decision of the Regulatory and Technical Council of the Ministry of Regional Development of Russia, Protocol № 1 of February 1st, 2011).

Thus for application on passenger or freight maglev line to be constructed, STCs can be designed which should contain a register of forced deviations from active normative documents of Russia and the Eurasian Customs Union, justification of these deviations, and requirements for compensating activities. STCs may also include separate provisions of other countries' norms, provided that those meet Russian legislation.

It needs to be pointed out that STCs may become the basis for design of Technical Regulations on maglev transport safety and forming of the register of standards and rules to support them. This register should be formed after certain active documents have been determined, the application of which is feasible without updating them, and those which can be applied after updating and processing, as well as identification of the documents to be designed.

DEVELOPMENT OF DRAFT STANDARD TECHNICAL CONDITIONS

Considering the described conditions, on the basis of the international experience and national practice of delivery of maglev transport projects, the authors of this paper together with other specialists have designed a complex (or set? No, it is exactly the "complex") of nine draft standard STCs for design of MLTS [1], retaining the possibility to adapt them to a certain passenger or freight line (Fig. 3).

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43
doi: 10.17816/transsyst20184432-43

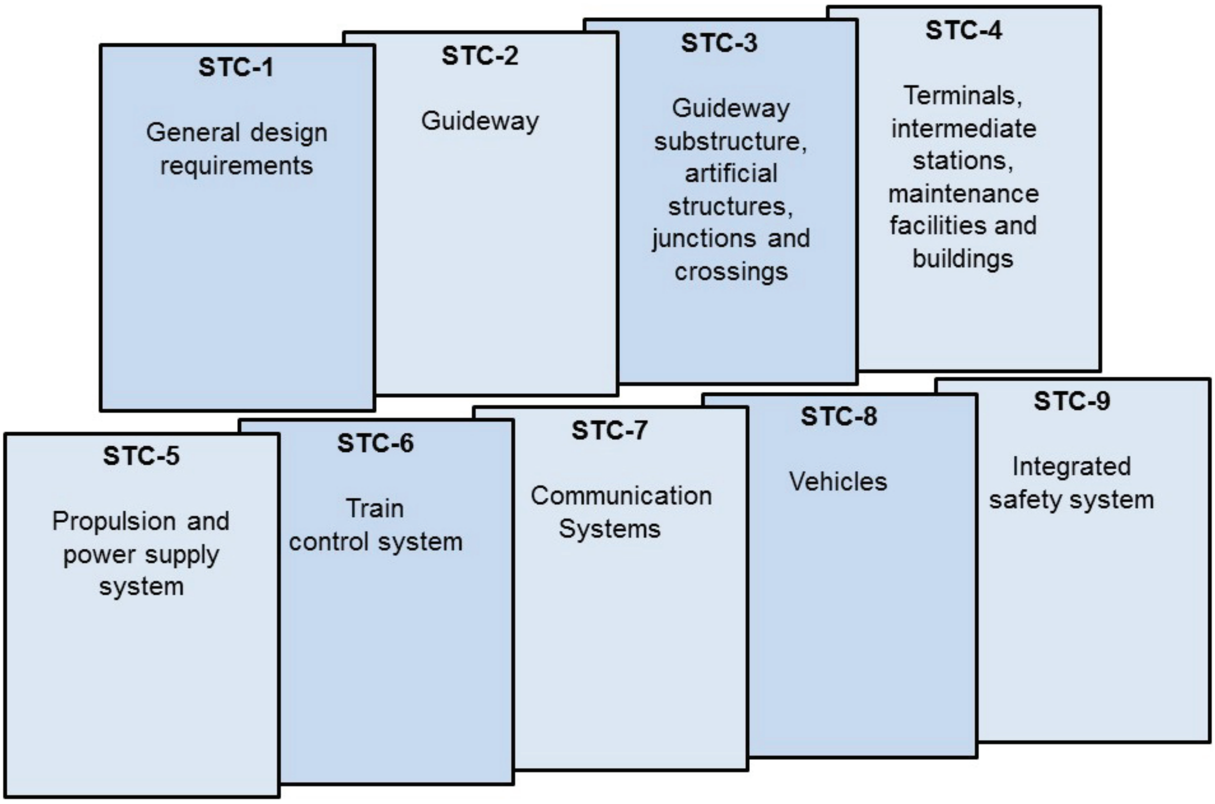


Fig. 3. Complex of draft standard STCs for maglev transport systems design

When designing the above-given STCs, apart from national developments and existing home-grown practice, the authors have broadly used the best international experience in this field. Thus, for instance, the details of requirements for MLTS design in terms of electromagnetic suspension are most comprehensively provided in the German Design Principles High-speed Maglev System. This is a major document [2], describing the Transrapid maglev passenger technology realised in Germany and China. The document provides requirements for the system as a whole, its vehicles, traction and power supply systems, operation control, and guideway. At the same time, the permanent magnet-based freight maglev transport technology, realised in USA by General Atomics, is described in the document [3] Conceptual Design Study for the Electric Cargo Conveyor (ECCO) System. Final Report. In a number of other documents, the descriptions of MLTS projects with various degree of realisation in different countries are given.

As a result of the study conducted, aimed at analysing and generalising the national and international experience, the English-Russian (Russian-English) Explanatory Dictionary was compiled, which contains terminology, definitions and requirements in design, construction and operation of maglev transport and may serve as a basis for preparation of a maglev transport course book.

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):32-43
doi: 10.17816/transsyst20184432-43

In the process of finalising STC and further working on standardisation of MLTS in Russia, it is necessary to use relative normative and technical documents (standards) of the countries that have already successfully delivered maglev transport projects: Germany (the European Union), USA, Japan, the Republic of Korea, China (Table 1).

Table 1. Standardisation systems of the countries (regions) that have realised maglev transport projects

Country (region)	**Standardisation system**
EU member states	Each country has its own standardisation bodies. In the case of Germany, for instance, its DIN. Any document that is issued by any standardisation institute to be applied in a certain EU state, is subject to harmonising at corresponding national and international levels.
USA	In USA the national standardisation system, including railway standards, are managed by ANSI (American National Standards Institute). However, ANSI does not design these standards but manages their design, performed by governmental bodies, commercial and non-commercial organisations. The USA standards can be roughly divided into the following basic groups: − mandatory standards, which are designed by governmental bodies (e.g. state defence sector) and which contain mandatory requirements; − voluntary standards, which are designed by organisations and concerns for application in a certain industry; − special standards, which have a more limited scope of application than the voluntary ones (the fact is that they are voluntary ones as well).
Japan	The Japanese Industrial Standards Committee (JISC). The country has active national industrial standards (JIS), industry standards of industrial associations, and corporate (company) standards. The national industrial standards, which are occasionally reconsidered, are voluntary and are specified in the form of industry standards. Corporate (company) standards are designed using national and industry standards, taking into account company's scope specifics and its products (services) delivered.
The Republic of Korea	The Korean Agency for Technology and Standards (KATS), which designs national standards (KS) in various industries.
China	The Standardisation Administration of China (SAC) undertakes management of standardisation. The Chinese national standards are divided into mandatory and voluntary. The latter one prevails, its application is encouraged in every way. Besides, China also employs the so-called "working standards" which validate the best practices of operation.

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):32-43

doi: 10.17816/transsyst20184432-43

At this point, special attention should be given to MLTS safety issues. The existing world practices of securing transport systems' safety builds on application of a priori (forecast) and a posteriori (technical operation processes monitoring) risk estimates, including analysis of cause-and-effect relations and identification of pre-failures, negative tendencies and risk prerequisites. To realise these methods, the European Committee for Electrotechnical Standardization (CENELEC) has developed a number of framework documents. Today, as international standards the documents such as EN 50126 (IEC 62278), EN 50128 (IEC 62279) and EN 50129 (IEC 62425) are applied as the Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) for transport systems and application guidelines. Apart from those, the standard to manage life cycle cost (Life Cycle Cost, LCC) IEC 60300-3-3 is also used (Table 2).

With regards to harmonisation of these documents in Russia, it needs pointing out that to date two national standards are approved:

• GOST-R MEK 62279-2016 Railways. Communication, signalling and data processing systems. Software for railway control and protection systems;

• GOST-R MEK 62280-2017 Railways. Communication, signalling and data processing systems. Safety related communication in transmission systems.

The developed project of GOST-R MEK 62278 (Determination and Confirmation of reliability, availability, maintainability and safety on railways) has not been approved as the national standard.

The issues relating to management of interrelated RAMS/LCC indicators, based on CENELEC approaches, have been reflected in the documents "Resources, risks and reliability management at life cycle stages" (URRAN)M which are undergoing implementation process at JSC "RZD", as well as in the following documents approved on their basis:

• GOST 33432-2015 Functional safety. Policy and programme of safety provision. Safety proof of the railway objects;

• GOST 33433-2015 Functional safety. Risk management on railway transport;

• GOST-R 33432-2015 Railway transport risks management. Classification of hazardous cases.

To interlink RAMS/LCC requirements with quality requirements in the unified business management system in an organisation, specialising in design, manufacture and operation of transport systems, the international standard ISO/TS 22163:2017 Railway applications – Quality management system – Business management system requirements for rail organizations: ISO 9001:2015 and

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):32-43
doi: 10.17816/transsyst20184432-43

Table 2. Updated versions of basic normative documents on transport systems RAMS/LCC

Item	Full title
BS EN 50126-1:2017 [4]	Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Generic RAMS Process
BS EN 50126-2:2017 [5]	Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Systems Approach to Safety
IEC/TR 62278-3(2010) [6]	Railway applications – Specification and demonstration of reliability, availability, maintainability and safety (RAMS) – Part 3: Guide to the application of IEC 62278 for rolling stock RAM
IEC/TR 62278-4(2016) [7]	Railway applications – Specification and demonstration of reliability, availability, maintainability and safety (RAMS) – Part 4: RAM risk and RAM life cycle aspects
IEC 62279(2015) [8]	Railway applications – Communication, signalling and processing systems – Software for railway control and protection systems
IEC 62425(2007) [9]	Railway applications – Communication, signalling and processing systems – Safety related electronic systems for signalling
PD CLC/TR 50506-1:2007 [10]	Railway applications – Communication, signalling and processing systems – Application Guide for EN 50129 – Part 1: Cross-acceptance
PD CLC/TR 50506-2:2009 [11]	Railway applications – Communication, signalling and processing systems – Application Guide for EN 50129 – Part 2: Safety assurance
PD CLC/TR 50451:2007 [12]	Railway applications – Systematic allocation of safety integrity requirements
IEC 62280(2014) [13]	Railway applications – Communication, signalling and processing systems – Safety related communication in transmission systems
IEC 60300-3-3(2017) [14]	Dependability management – Part 3-3: Application guide – Life cycle costing

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184432-43

particular requirements for application in the rail sector is used. This document [15] is an updated version of the International Railway Industry Standard (IRIS).

CONCLUSION

Standardisation in Russia is expected to fully realise the key competitive advantages of maglev transport: fast passengers and freight delivery, higher capacities (at the expense of increased automation, i.e. "transport conveyor"), independency from external factors (other transport modes traffic, weather), adaption to landscape features, namely urban areas (as compared to conventional railway transport), low power consumption in the case of permanent magnets application (absence of rotating elements and transmission mechanisms), constant technology improvement and decrease of construction cost, environmental safety (low noise, vibration and dust pollution, urban compatibility), lack of barriers, which is natural for railways and highways.

The work should be continued to form the national technical regulatory framework for design, construction and operation of MLTS on the basis of international experience and national practice of delivery of MLTS projects.

Библиографический список / References

1. Шматченко В.В., Плеханов П.А., Роенков Д.Н., Иванов В.Г. Подготовка специалистов и разработка нормативной базы проектирования магнитолевитационных транспортных систем в России // Транспортные системы и технологии. – 2018. – Т. 4. – № 1. – С. 138–154. [Shmatchenko VV, Plekhanov PA, Roenkov DN, Ivanov VG. Training of Specialists and Development of Design Regulatory Framework for Russian Magnetic Levitation Transport Systems. *Transportation Systems and Technology.* 2018;4(1):138-154]. doi: 10.17816/transsyst2018041138-154.
2. Design Principles High-speed Maglev System (MSB). Information. Germany: Federal Railway Authority; 2008.
3. Conceptual Design Study for the Electric Cargo Conveyor (ECCO) System. Final Report. General Atomics (GA): Prepared for The Port of Los Angeles San Pedro, CA; 2006 October 27. Agreement No. E-6304. GA Project 20132.
4. BS EN 50126-1:2017 Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Generic RAMS Process.
5. BS EN 50126-2:2017 Railway Applications – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) – Systems Approach to Safety.

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184432-43

6. IEC/TR 62278-3(2010) Railway applications – Specification and demonstration of reliability, availability, maintainability and safety (RAMS) – Part 3: Guide to the application of IEC 62278 for rolling stock RAM.
7. IEC/TR 62278-4(2016) Railway applications – Specification and demonstration of reliability, availability, maintainability and safety (RAMS) – Part 4: RAM risk and RAM life cycle aspects.
8. IEC 62279(2015) Railway applications – Communication, signalling and processing systems – Software for railway control and protection systems.
9. IEC 62425(2007) Railway applications – Communication, signalling and processing systems – Safety related electronic systems for signalling.
10. PD CLC/TR 50506-1:2007 Railway applications – Communication, signalling and processing systems – Application Guide for EN 50129 – Part 1: Cross-acceptance.
11. PD CLC/TR 50506-2:2009 Railway applications – Communication, signalling and processing systems – Application Guide for EN 50129 – Part 2: Safety assurance.
12. PD CLC/TR 50451:2007 Railway applications – Systematic allocation of safety integrity requirements.
13. IEC 62280(2014) Railway applications – Communication, signalling and processing systems – Safety related communication in transmission systems.
14. IEC 60300-3-3(2017) Dependability management – Part 3-3: Application guide – Life cycle costing.
15. ISO/TS 22163:2017 Railway applications – Quality management system – Business management system requirements for rail organizations: ISO 9001:2015 and particular requirements for application in the rail sector.

Information about the authors:

Pavel A. Plekhanov, Candidate of Engineering Science, Associate Professor;
9 Moskovsky av., St. Petersburg, Russia, 190031;
eLibrary SPIN: 1532-9427; ORCID: 0000-0002-2546-259X;
E-mail: pavelplekhanov@gmail.com

Vladimir V. Shmatchenko, Candidate of Engineering Science;
eLibrary SPIN: 5152-2090; ORCID: 0000-0001-6963-7286;
E-mail: vshmat45@mail.ru

Сведения об авторах:

Плеханов Павел Андреевич, кандидат технических наук, доцент;
Россия, 190031, г. Санкт-Петербург, Московский пр., д. 9;
eLibrary SPIN: 1532-9427; ORCID: 0000-0002-2546-259X;
E-mail: pavelplekhanov@gmail.com

Received: 01.10.2018. Revised: 30.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184432-43

Шматченко Владимир Владимирович, кандидат технических наук;
eLibrary SPIN: 5152-2090; ORCID: 0000-0001-6963-7286;
E-mail: vshmat45@mail.ru

To cite this article:
Plekhanov PA, Shmatchenko VV. Standardization of Maglev Transportation Systems in Russia. *Transportation Systems and Technology.* 2018;4(4):32-43. doi: 10.17816/transsyst20184432-43

Цитировать:
Плеханов П.А., Шматченко В.В. Стандартизация магнитолевитационных транспортных систем в России // Транспортные системы и технологии. – 2018. – Т. 4. – № 4. – С. 32–43. doi: 10.17816/transsyst20184432-43

DOI 10.17816/transsyst20184444-63

© A. Santangelo
Consulting Structural Engineer
(Catania, Italy; Las Vegas, USA)

HYPERLOOP AS AN EVOLUTION OF MAGLEV

Hyperloop is often described as the "fifth mode of transportation" but, as the race between competing companies around the world intensifies, investors, governments and scientists remain cold and cautious. An educated guess from one of the first civil engineers involved with the design of a real-world hyperloop infrastructure tries to give some direction between hype and pragmatic design.

Keywords: Hyperloop, vacuum transportation, future transportation, tubes, civil engineering design, infrastructure

INTRODUCTION

In August 2013, Elon Musk (CEO of Tesla & SpaceX) and SpaceX released an Alpha study detailing a new form of transportation called the Hyperloop "*a fifth mode after planes*, *trains*, *cars and boats*". The Alpha study was intended to promote an alternative transportation system, after the California High Speed Rail proposed design.

Among various innovative design concepts, the study claimed that the Hyperloop could cover the 560 km distance between Los Angeles and San Francisco in an estimated time of 35 minutes, at an average speed of 970 km/h and a maximum of 1200 km/h, in contrast to the 2 hours and 38 minutes of the California High Speed Rail proposal, or the hour and 15 minutes of airplanes.

The Musk Hyperloop capsules are able to reach near Mach speeds by travelling through a low-pressure tube (approximately 100 Pa) and thereby minimizing the influence of drag and resistive forces.

That 2013 report marked the restart of the transportation technologies based on vehicles running inside an almost-vacuum environment. It was a restart because this concept has nothing revolutionary: More than one hundred years ago the Russian professor Boris Weinberg from Tomsk Institute of Technology developed the project of a train in which the cars would run inside an evacuated copper tube held up in the air by electromagnets and steering clear of its walls. Sources at Tomsk University explained that the project was hardly conceivable in the early 20th century and could not be put into practice because of the costs involved.

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

From that time several concepts of vacuum transportation flourished around the world, having all similar main features.

Even Musk's white paper was often criticized to give oversimplified solutions to complex issues, it ignited new lifeblood to the stagnant and often lazy general concept of already established forms of transportation. While the industry and media had an overall positive and sometimes even enthusiastic response, the academic world reacted with cold and sometimes even conflicting opinions.

1.0. HYPERLOOP AS AN EVOLUTION OF MAGLEV

Magnetically levitated trains are undoubtedly the most advanced vehicles currently available to railway industries. Maglev is the first fundamental innovation in the field of railroad technology since the invention of the railroad. Maglev vehicles use noncontact magnetic levitation, guidance and propulsion systems and have no wheels, axles and transmission. Contrary to traditional high-speed railroad vehicles, there is no direct physical contact between maglev vehicle and its guideway. These vehicles move along magnetic fields that are established between the vehicle and its guideway. Conditions of no mechanical contact and no friction provided by such technology makes it feasible to reach higher speeds of travel attributed to such trains.

Even is not obviously the intent of this report to go into details about the Maglev technology, it is needed to define the two main suspension groups:

- Electromagnetic Suspension (EMS);
- Electrodynamic Suspension (EDS).

Both suspension systems show the same main features as safe travelling at high speed, low pollution because of electrically powered, low maintenance and high capacity to accommodate increasing traffic growth, but they are technically very different.

Performance of EMS system is based on attractive magnetic forces, while EDS system works with repulsive magnetic forces. In EDS system, the vehicle is levitated about 10 mm to 100 mm. above the track using Permanent Magnets (PM EDS) or Superconducting Magnets (SC EDS). In EMS system instead, the vehicle is levitated about 10 mm to 20 mm above the guideway using electromagnets.

The highest speed reached with a Maglev train is (at the present time) equal to 603 km/h and it was possible to achieve it using passive SC EDS technology adopted by the Japanese high speed L0 train series owned by JR Central (Central Japan Railway Company). The train uses the superconductivity phenomenon to obtain zero electrical resistance and thus a very powerful magnetic force. The magnets on board the vehicles achieve a superconducting state by cooling a niobium-

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

titanium alloy with liquid helium to a temperature of – 269°C. The Propulsion, Levitation and Guidance systems are all installed in the sides of the guideway. Although the system is extensively tested and reliable, the costs of construction and operative are almost proibitive. Besides, due to the aerodynamic drag, its speed record might be not easy to outmatch.

Indutrack

The need to develop a simpler and cheaper Maglev led the USA to design the *Inductrack*, a technology that uses also passive EDS but with the adoption of Neodymium-Iron-Boron permanent magnets instead superconducting magnets.

In this design, an array of permanent magnets (Halbach Arrays) is located on the bottom of the vehicle that create a magnetic repelling field when they pass over passive coils on the rail bed. Each coil is a closed circuit, not connected to other coils or to an external power source. Thrust from linear motors propels the pods forward.

Hyperloop

All open air systems face a simple problem: aerodynamic drag. If we consider Maglev, it faces a lot of drag as speed increases. The drag forces quadruple as the velocity of the object doubles, and, to overcome that drag force it needs eight times the power to increase its speed. Thus drag limits the top speed for ground-based open air systems.

Hyperloop has been designed to overcome this. By operating in a low-pressure environment that allows for lower air density the system limits the amount of drag it would face to begin with. This coupled with a passive levitation system to eliminate friction and a compressor to channel the air in front of the capsule and funnel it to the back to generate extra thrust. The compressor is driven by an electric motor which gets its power from onboard rechargeable DC batteries.

In order to achieve very high speeds, the adoption of a linear induction motor (LIM) is the most efficient way to produce frictionless thrust able to overcome the aerodynamic drag.

Solar panels eventually cover the tubes structure to recharge the DC batteries. Standard commercial pumps could easily overcome the air leak and maintain the low pressure needed in the tube. The LIM is clean, and its maintenance is easy as it has no moving parts or gears.

While Hyperloop technology promises to be a highly innovative transportation mode that could enable true high-speed ground transportation, the development of the technology is still in early stages. The system is a large-scale engineering project, with development continuing on all elements of the vehicles and infrastructure, including propulsion systems, levitation systems, guidance and control, signaling, thermal and so on.

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184444-63

This technology is moving quickly, but will require coordination and acceptance from regulatory agencies on design, operations, security, and safety.

In the next sections of this paper it will discussed and briefly analyzed the main subsystems of the Hyperloop infrastructure.

2.0. TUBES STRUCTURES DESIGN

The Hyperloop superstructure is basically the tubes structure. It could be easily considered as a multi-span continuous bridge with the typical requirements that are prescribed for the high-speed railway system or even more stringent for the Maglev system.

2.1. SPACING ALIGNMENT AND CURVES

The vacuum tubes structure could be designed to be built overhead on pylons, at ground level, shallowly below ground, or deeply below ground, in accordance with existing terrain conditions and the requirements on the radius of curvature. Each method has its advantages and disadvantages. This paper will consider the elevated configuration of the vacuum tubes supported by piers. In this case the tubes structure is supported by a substructure at a regular distance and the loads are transferred to the pier with the adoption of structural bearings which constrain the tube in the vertical direction but allow longitudinal slip for thermal expansion as well as dampened lateral slip to reduce the risk posed by earthquakes.

Spacing

The spacing of the piers retaining the tubes is critical to achieve the design objective of the whole structure. In general, an optimal span length exists for elevated structures. Shorter spans reduce superstructures cost, but increase overall column, footing, and earthwork costs as more columns and footings are required for a given distance. In the infrastructure industry the average span is usually between 20 m to 40 m and, according to Musk's white paper *Hyperloop Alpha*, the spacing was considered equal to 30 m. The adoption of this span would make the static loads acting on the piers still quite reasonable due to the lightweight of the Hyperloop tubes and the vehicles, but the dynamic amplification loads could be very large due to the very high travel speed of the running vehicle.

Alignment

Most of the classical transportation systems on wheels have such gradients that do not cause relevant difference between the real 3D alignment and its projection on the horizontal plane. The Hyperloop system instead (as well as

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

the Maglev) can go up to steep gradients (up to 10–15 %) and need then a very precise alignment stationing to be defined in 3D to provide exact location of the levitation equipment, precise evaluation of the centrifugal forces along to achieve comfortable and safe riding during accelerations/deceleration conditions. The use of height variation could sometimes be the only solution to achieve comfortable curves while keeping the desired design speed.

Curves

The curve radius has a strong influence during the alignment design because lateral g-forces above 0.5 g are usually considered not acceptable for comfort reasons.

The lateral acceleration of the curve increases with the square of the velocity and decreases with the turn radius, which results in a simple relationship between turn radius and vehicle velocity; as an example then, we can deduct that at maximum Hyperloop operative speed the tubes structure must bend at a minimum radius of 23.5 km to be comfortable for the passengers (Alpha document). It is then clear that this is one of the limitations to take in account during the design of the alignment because it gives limitations both on bending radius and the operative speed. Plausible alternative is to use a banking mechanism for the capsule as it goes around a turn. Yet, banking achieves less lateral acceleration at the expense of greater perceived vertical acceleration, which can give humans the sense of sea sickness. It may be possible to manipulate the height of the pylons to still reduce the resultant lateral accelerations while banking and transfer these to longitudinal, not vertical, accelerations that are tolerable.

The geometry where the Hyperloop structure can transition into curves from a tangent and the alignment geometry requirements could be generally comparable to the standard high-speed systems while the banking angles usually used to accommodate curve radii are not comparable since on Hyperloop system might be more limited. One of the most suitable transition curves that Hyperloop could benefit is the sinusoidal transition approach as it is described in the Eurocode norm for track Alignment EU 13803:1

The sinusoidal curve (also called "*Klein*") provides smooth variation for the vertical and lateral jerk, without the sudden changes found for most of the transition curves, including the clothoid and linear. This smooth variation is an essential requirement in defining the alignment of the system. The design must not experience uncomfortable lateral or vertical g-forces and jerks through any curve.

2.2. DEFLECTIONS

An important guideway design issue for any elevated bridge-like infrastructure is the maximum deflection that can be allowed on each span. To ensure adequate

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

ride quality, allowable beam vertical deflections due to beam dead weight as well as to all live loads are limited. Most commonly, static deflection criteria are presented as a ratio of the span length over a set numerical value, e.g. L/2200 for span greater than 10 meter is a vertical deflection limitation imposed by California High Speed Rail design criteria; Transrapid is set to L/4000. The deflection criteria must consider restrictions for both short and long-term behavior. Short-term deflection behavior is calculated according to elementary beam while long term deflections, due to material creep, shrinkage, and/or relaxation, are estimated as a percentage increase of short term beam deflection calculations.

When analyzing the vertical deflection limitations of the Hyperloop system, the roughness A, and its effect on passenger ride quality, the maximum dynamic vertical and horizontal deflections are perhaps more appropriate criteria measures since they are generally larger and more significative than static deflections. The dynamic deflections depend on several parameters among which are the natural frequencies of the tube structures, the vehicle dynamic properties, speed and even the vehicle throughput.

2.3. LOADS

Load effects typically refer to tube structure deflections resulting from static and dynamic forces and moments exerted on portions of the tubes structure. In addition, thermal expansion and contraction tendencies of the tubes can cause bowing and warping if allowances (e.g. sliding bearings) are not made for such movements. The acceptable tubes structure design must be capable of resisting all load effects within the constraints necessary for acceptable and safe system operation.

Dead weights

Dead loads are permanent gravitational loads on the structure due mainly to the density of the tube members. Other dead loads include the suspension magnet system, the track insert, the guidance magnet system, the cabling, insulation layers and so on. All those loads are usually considered uniformly distributed on the tube structure and are almost all located in the lower part of the tube

Normally, mostly of the dead loads result in an initial deflection of the beam. Depending on the construction material and technology of the tubes, we can also consider as permanent loads the pre-tension forces, the creeping and shrinkage. The dead loads of the auxiliary components of the tubes structures, they should be determined according to the relevant standards and regulations.

Vacuum

To reduce the drag force and manage shock waves as the capsule approaches the speed of sound, the Alpha paper suggest to set the operating tube pressure to

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

100 Pa (1000 times less than sea level conditions). This negative pressure will act radially inside the tube walls and it must be kept constant.

Vehicle loads

Vehicle loads can range from uniformly distributed to concentrated point loads, depending on the loading pad configuration of the vehicle. Though any vehicle loading pad arrangement can be accommodated in the tube structural design, as size and strength requirements for the tubes are influenced by the distribution of the vehicle loading, the more distributed the load, the lower the tube structural strength requirements will be. Moreover, a more distributed loads will generally lower the dynamic effects.

Acceleration and Braking

The speed of the vehicle can be continuously regulated by varying the frequency of the alternating current of the propulsion system (e.g. LIM–Linear Induction Motor). If the direction of the traveling field is reversed, the motor becomes a generator which brakes the vehicle without any contact and the braking forces will act in the same trackside of the propulsion forces. It could also use a friction brake mechanism against the rails located on the interior tube wall for low-speed motion or emergency. Using as reference *the Maglev Construction and Operation Ordinance* (MbBO) the acceleration limits are set to 1.5 ms^{-2} for the drive, braking acceleration and lateral acceleration while for the normal acceleration is limited from –0.6 ms^{-2} to +1.2 ms^{-2} as comfort value.

Lateral force due to guidance

To make the vehicle laterally stable during the travel, there is a guidance system that will exert a force dependent with the velocity of the vehicle. This force should be considered during the design of the tube structures.

Centrifugal force

This force acts horizontally and with the direction perpendicular to the tangent to the horizontal axis of the guideway. It will cause moment around the longitudinal axis that will be transferred over the levitation magnets to the tubes structure. The tubes structure will load the bearings with axial tension and compression forces.

2.4. THERMAL

Thermal load effects are very significant in an Hyperloop structure. In case the support system is designed as constrained, changes in temperature induce additional thermal stresses on the tube structures. While instead the a simply supported scheme is chosen, the horizontal displacements must be accommodated by expansion joints with adequate displacement capacity. The bowing and warping

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

of the tubes must be always avoided since they can develop uplift forces on the piers or/and excessive lateral and vertical deflections.

International codes often prescribe to increase of the environmental thermal loads by 1.25 for the design of the expansion joints and structural bearings. Hyperloop tubes structure should take in account at least the similar amplification factor.

Structural elements composed of materials having similar thermal expansion coefficients expand and contract uniformly, e.g. steel and concrete. In contrast, structural elements containing materials having significant differences in thermal expansion properties expand and contract non-uniformly. This non-uniform thermal behavior typically leads to internal thermal stresses, and potentially, to bowing of the element. The design of the tube structures should take in account this issue.

Thermal and blockage ratio

Some recent research studied the thermal-pressure coupling effect on blockage ratio in the almost-vacuum tubes structure. The results showed that when the speed of the vehicle and system pressure are held constant, the aerodynamic heating increases exponentially as the blockage ratio (the ratio of the outer projected area of the vehicle to the cross-sectional area of the tube) increases. Aerodynamic heating is caused by the vehicle friction with the surrounding medium at the high speeds. As the clearance between the capsule and the tube wall becomes smaller, more intense collisions and mixing of airflow occurs as well as more airflow viscous friction with the surface of the capsule, causing the temperature of the whole system to increase. A large amount of heat generation caused by the capsule can be harmful to the system's operation.

Detailed CFD (Computational Fluid Dynamics) thermal Analysis of the tubes structures should be carried on investigating the optimal blockage ratio to avoid the potential temperature increase that could arise from the aerodynamic heating of the vehicle at very high speed inside the tubes.

3.0. SECONDARY ELEMENTS DESIGN

In this section will be briefly described some of the secondary elements to be considered during the design of the Hyperloop infrastructure

3.1. EXPANSION JOINTS

Thermal expansion has been a problem with large tubular structures for a long time. Oil pipelines use various technologies to overcome this obstacle, with one such solution being expansion loops. The loops provide a necessary extension

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

of piping in the perpendicular direction of fluid flow to absorb thermal expansion. Safer than expansions, they however occupy more space and they are impracticable solution for an Hyperloop system.

The *Hyperloop Alpha* white paper, while presenting the proposed route stretching from San Francisco to Los Angeles, considers slip-joints as an answer to this problem, however many of the technicalities have yet to be addressed. Considering that track, constructed from steel, and assuming standard values for thermal coefficient of steel and a temperature range of 0 °C to 40 °C, means that the track would need to expand by approximately 300 m to accommodate the full range of temperatures. Slip joints could be placed at the stations, but that would mean the joints and stations would need to be able to move by 300 m.

Another more feasible option is to space these out incrementally, which means incorporating several structural expansion joints along the track. They would be located over support piers or abutment seats.

The design of the optimal Hyperloop expansion joint must take in account three basic requirements:

• Accommodate horizontal large displacements;
• Ensure the operational “almost vacuum” status;
• Satisfy the continued functionality under earthquake design forces.

Depending on the displacement capacity needs the expansion joints could be manufactured using elastomeric bellows or a more complex telescopic design to accommodate larger displacements.

Another issued related to thermal loads is buckling stresses due to the difference in temperature between the top and the underside of the steel tube (temperature gradient). In any sunny area where Hyperloop is intended to deploy (Los Angeles, Dubai etc.), the top surface of the tube will heat up and hence expand more than the underside of the tube. This could transform the circular cross-section into a mushroom-like shape. This would not only affect the structural integrity of the tube itself, but also the internal components required to maintain smooth travel of pods and could cause contact between the pod and the tube.

3.2. SUBSTRUCTURES

The purpose of the tubes substructures is to bridge the height difference between the tubes and the ground (through bearing supports) and to transfer forces from the superstructures to the foundations taking system-related requirements into account. Concrete and steel designs are both acceptable columns even the concrete is undoubtedly the optimal solution. Better if used with post-tensioning

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

technology. The foundations are generally made in concrete adopting a deep pile design to limit the settlements.

General Functional requirements

The influential functional requirements for guideway substructures are:

• The substructures must directly support the actions from the tubes structure via the support bearings and reliably transfer them to the foundations;

• Tubes equipment components, modules and ausiliary structures (e.g. safety fire escapes and maintenance structures) must be reliably incorporated;

• Tubes substructures must permanently guarantee the required positional accuracy of the superstructures.

General Design requirements

The following design requirements must be considered when designing the substructures:

• Vertical frequency analysis that will be performed during the design of the hyperloop structure shall consider the flexibility of bearings, shear keys, columns, and foundations; torsional frequency analysis shall consider them as well;

• Substructures permissible deformations along the three axes must be considered as part of the design; limitations required by norms of high speed rail or Maglev systems have strict limits that can be as low as L/4000). When the permissible deviations in the positions of substructures are exceeded (subsoil long term assessment, earthquake movements, etc.), readjustment of the support bearings is necessary for ensuring system compatibility;

• When designing the foundation system, the high loading velocity and dynamic forces (frequency, amplitudes) from the tube structures mist be also observed – extensive theoretical and/or empirical studies of the soil behavior must be required;

• Safety devices must normally be included according to the project-specific safety concept to prevent impact of vehicles and devices on crossing and parallel routes;

• Separate substructures for consecutive tube structures should be avoided.

Support Bearings

The design development of the tubes structure support bearings is to be selected in connection with the static layout of the complete superstructure and substructure system. Suitable supporting systems are to be selected in accordance with the static system of the tubes (e.g. simple supported vs continuous).

The determination of the support arrangement (sequence fixed-/loose supports) of tubes structures spans following on from each other and in connection with the installation of the support bearings requires verification of compatibility with the complete system. The vertical and horizontal stiffness must be adequate to make the system stable during operative conditions. In case of rare actions and

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184444-63

combination of actions it is possible to guarantee the required positional stability via additional devices which are normally not required in normal operation (e.g. Lock-Up devices and Fail-Safe devices).

In case of use of moving friction-controlled bearings (e.g. sliding bearings or Friction Pendulum bearings) the friction coefficients accepted in the dimensioning of the bearings are to be indicated by giving their functions and value limits. The friction coefficient values given are to be proven and tested. The speed of movement of the supports (low speed-high speed) is to be taken into account in the theoretical estimation of the wear of the bearing support system (verification of serviceability).

Maintenance of support bearings

The support bearings are to be developed in such a way that the tube structures can be adjusted in the shortest possible time at the lowest possible cost in the case of subsidence. The degrees of adjustment are to be prescribed specifically for the project. If the admissible value limits of the deformations and displacements are exceeded, a balance should be aimed for by adjusting the supports. If this is not possible a simple exchange of the wearing parts must be guaranteed.

In the case of direct connection of the tube structures to the pier substructures (e.g. in the case of direct casting of the bearing steel plates to the substructures) the durability and safety is to be guaranteed by a robust and error tolerant design.

For carrying out repairs to supports the tubes should not be raised more than 5mm. The location of presses for raising the tubes structure is to be defined and marked on the tubes.

4.0. MATERIAL REQUIREMENTS

The selection of the most suitable material (or materials) is undoubtedly one of the fist challenges associated with the design of the tube. To match the expected low maintenance and great durability of the Hyperloop system, the tubes structure should be constructed of materials that have a longer life than conventional structures. Moreover, to make construction faster and less expensive, prefabricated support columns and tube spans should be considered.

Along with the mechanical properties associated on each structural material, there are some essential characteristics that the Hyperloop tube structure must perform.

Mechanical Properties

Of the three primary mechanical properties, strength, stiffness and damping, stiffness is expected to dominate any static analysis and is the primary design

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

constraint. Dynamic loading effects increase the importance of structural damping characteristics for the overall tube design. The tendency for damping constraints to exceed stiffness constraints depends on the dynamic behavior experienced by the tubes. Passive damping of 2 % to 5 % should be achievable through proper material selection. The potential amount of damping possible could be managed with the use of active and passive devices (e.g. dampers) that could possibly be adjustable in function of the dynamic loads imposed by the speed of the vehicle to additional ride quality improvements.

Operational properties

A major technical challenge associated with the tube design is how to ensure that the entire length is kept airtight. Any ruptures or openings in the tube might result in a large pressure difference and a shock wave will propagate along the route. This essential property must be guaranteed in a long-term condition, as well as must be guaranteed also creep, shrinkage and relaxation. Other operational properties should include also high fire protection rating and magnetic inertness.

4.1. CONVENTIONAL MATERIALS

The civil engineering standards recognize two basic materials: Concrete and Steel. Each one of them has pros and cons that should be considered and evaluated for the Hyperloop superstructure.

Concrete

Concrete is a versatile material and has the main advantage to be easier to manufacture and is undeniable cheaper than steel. But it lacks tensile properties and needs thou the steel rebars to compensate this deficiency. It has somehow a shorter life than steel under several physical and chemical processes as well as certain environmental conditions that may deteriorate its resistance in a short period of time. Concrete is nowadays often used with prestressing technology, that improves in a more efficient and economical way the structural performance of the superstructure. One of the main disadvantages of the concrete is its porosity. Using the concrete for the tube structure could pose the risk of a leak due to potential outgassing that might compromise the sealing of the tubes during the service life. This issue although could be controlled with the adoption of sealing layer or special additive in the concrete mix.

Steel

Steel has a higher resistance than concrete; it has excellent tensile and compressive behavior but is way more expensive than concrete.

It is usually more durable than concrete even if, under certain environmental and chemical conditions could be easily deteriorated as well. Steel superstructures

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

are usually lighter than concrete alternatives, but the material savings are often be offset by the complexity of manufacture, the steel costs, and usually they perform a reduced structural efficiency in the connection between superstructure and substructure. Steel has thermal expansion characteristics similar to that of concrete and therefore is an excellent reinforcing material for concrete. One of the problems associated with steel structures is the corrosion and magnetic interference potential.

4.2. COMPOSITES AND HYBRIDS

Composites

Fiber reinforced polymer, FRP, is the most promising of the composite materials for use in structural applications. Fibers typically used are boron, carbon, glass and aramid. Boron and carbon are extremely expensive. Aramid is somewhat less expensive but has low compressive strength. Glass (GFRP) is relatively inexpensive, has high strength, but is only one quarter as stiff as mild steel. For flexural design of the tube structures stiffness is likely to be the primary base of comparison between CFRP (Carbon), especially the high modulus (HM) and high modulus (UHM) CFRP, though roughly equal or even superior to mild steel in stiffness, has three to four times the strength. Major drawback of all those composites is often related to the directional e strength of the properties. Unlike isotropic materials (like steel) the properties of GFRP or CRFP depend on the layouts of the fibers.

Another viable solution of composite material is the adoption of the concrete composite structure with a thin metal layer. Because the inside steel layer will want to be pushed away from the concrete layer, special attention needs to be directed to securing it in place. This may be a challenge to avoid. The overall thickness of the tube may be larger with this composite structure, but the cost will be less than a steel tube since concrete is much cheaper than steel. This structure will have large compressive strength to allow for a more intense vacuum degree. A stainless steel layer could also be added to the outside of the concrete to help mitigate damage and corrosion. This layer would tend to be pulled against the concrete layer, making the fastening much easier.

Hybrids

One of the most successful hybrid materials that is currently being adopted in various civil engineering project is called Ultra High-Performance Concrete (UHPC).

This material is basically a concrete that uses a relatively high binder ratio, has a water-to-cement (w/c) ratio of 0.24 and lower, and has a compressive strength in excess (150 MPa). Low matrix porosity and high particle packing density leads

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

to significantly higher durability at a similar unit weight compared to conventional concrete. The addition of discontinuous fibers reinforcement (organic or steel) leads to significantly higher ductility, durability, high flowability (self-consolidating), higher mechanical properties (high tensile properties) and durability. The UHPC is usually manufactured with steel fibers although there are also commercially available some varieties that use glass fibers that could reach even higher strength and durability properties.

Compared to traditional concrete, the UHPC reduces substantially the typical degradation like outgassing and microcrackings due to the low water content and the high tensile properties.

5.0. DYNAMICS

The current state-of-practice for the design and dynamic behavior assessment of the typical high-speed rail infrastructures is comprehensively studied in several norms and codes around the world. However, the dynamics is usually explored for train speeds that often reach no more than 200 km/h. Chinese codes issued by the Ministry of Railways of PRC refers to 350 km/h as top speed while the Maglev design basis guideway (*Magnetschnellbahn Ausführungsgrundlage Gesamtsystem*) from the EBA – German Federal Railway Authority, gives some very useful indication and guidelines for speed up to 450 km/h. The operative speed of an Hyperloop system is more than double of the highest speed ever considered in any actual released code so there is a need to set some rigorous dynamic analysis to understand the dynamic interaction between the tube structure and the vehicle. At Hyperloop speed a flexible tubes structure is usually less expensive but could cause a very complex interaction problem and could affect ride quality as well. The scope of the dynamic analysis is to optimize the whole Hyperloop system: the vehicle with its suspension and active control characteristics in one side and the tubes structures with its flexibility in the other side. The elements essential of an interaction model are as follows:

1) Vehicle Dynamics;
2) Vehicle Suspension and Guidance;
3) Surface Roughness;
4) Tubes structure Dynamics;
5) Bearings Support and Soil Dynamics.

As the vehicle travels inside the tube, suspension system forces and guidance system forces, which causes various linear and rotational accelerations. The suspension system responds to vehicle motion, the tubes structure dynamics and surface irregularity. The tubes structure forces the bearings support and they transfer

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

(and filter sometimes with specific stiffness and damping) the loads through the substructures and interact eventually with the soil dynamics. These systems interact with each other through time varying interfaces. The strongly coupled process is extremely complicated.

Since the details of the computational dynamic analysis is beyond the scope of this paper, here it will be shown the civil engineering approach in considering the dynamic effects on the tube structures and some reference to vehicle dynamics.

5.1. RESONANCE AND DYNAMIC AMPLIFICATION FACTOR (DAF)

According to the fundamental theorems of structural dynamics, when a moving load (or a train of moving loads) travels over a bridge (or tubes structure in our case), the loading frequency (basically dependent on the vehicle speed and bridge span) will change with the vehicle speed and a resonant vibration will occur when the loading frequency coincides with the natural frequency of the structure. The strong vibration induced by the resonance not only directly affects the working state and serviceability of the structure (higher stress and deflections), but also reduces the running safety of the vehicle, diminishes the riding comfort of the passengers, and sometimes even destabilizes the structure itself. Therefore, it is necessary to develop methods to predict the resonant speeds of the running loads and to assess the dynamic behavior of the structure under resonance conditions.

Dynamic Amplification factor

The dynamic amplification factor (DAF) or sometimes called also impact factor IM, is an important parameter that it is often used in the codes during the design and assessment of the dynamic behavior of bridge structures in the absence of detailed dynamic analysis, simply by magnifying static deflection. This parameter is defined as the ratio of the maximum mid-span deflection of the bridge caused by dynamic conditions to the deflection induced by the static loads. Resonance is often related with the maximum DAF. In general, DAF is not a deterministic value and must be estimated through probabilistic methods.

Several numerical simulations performed with MATLAB-SIMULINK, or even using more focused FE bridge software like SAP2000 to perform time-dependent nonlinear modal analyses with an emphasis on tube dynamic deflection under a moving vehicle at various velocities, show that the DAF of the vertical deflection and bending steadily increase (after reaching a speed threshold) in proportion to the vehicle speed. In addition, it is observed that the DAF for the deflection is almost the same as that for the bending moment at the low and medium speed, but the deflection's DAF is higher at the high speed. Some established code

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184444-63

references suggest, for simple supported span structural scheme, to use maximum DAF:

- AASHTO LFRD: DAF=1.33 (*not depending on speed or span*)
- Transrapid (DE): DAF=1.56 max speed 500 km/h span=25 meters
- General Atomics: DAF=1.50 max speed 200 km/h span=36 meters

For the hyperloop system, with a range of speeds up to 1200 km/h and a span of 25 meters some studies evaluated the theoretical DAF close to 1.8.

This large value of DAF and the lack of dedicated studies of moving vehicles at very high speeds suggests that detailed dynamic analysis should be performed with robust and reliable analytical models since the early stage of the design, because the basic parameters of spacing and tube stiffness are strictly involved. The model should take realistically in account at least the tubes structure (material, geometry and spacing), stiffness, damping, single vs continuous spans and hopefully also some information related to the substructures like geometry and stiffness. The model should investigate the dynamic behavior of the system both at low and high travel speed.

5.2. VERTICAL DYNAMIC ACCELERATION

For the level of speeds that an Hyperloop system can reach, the ride quality is of highest significance since the extremely high operating speeds may result in discomfort to the passengers. Together with the evaluation of the dynamic behavior of the tubes structure, the vertical acceleration of the vehicle should be carefully evaluated. While for the evaluation of the dynamics of the tubes structures (and DAF calculations) the vehicle might be represented with just moving forces, in this case the analytical modelling of the vehicle must include its lumped mass and two suspension systems: the primary or magnetic suspension comprising of primary stiffness (k_p) and primary damping (c_p) and the secondary suspension comprising of secondary stiffness (k_s) and secondary damping (c_s). The primary suspension acts between the levitation frame and the tubes structure, while the secondary suspension is between the levitation frame and the vehicle. The suspension of such a vehicle must be designed not only to perform the role of guidance and support but also to isolate the vehicle from any random disturbances arising from track irregularities (roughness of the track). Using Signal processing Tools provided in SIMULINK, a Gaussian white noise could be generated and then passed through a specified infinite impulse response (IIR) filter to get the desired guideway irregularity. The vehicle vertical acceleration magnitude is an indication of vehicle ride quality and it should be always verified that is will stays within the limits of human comfort. The range of acceptable vertical acceleration is -0.6 ms^{-2} to $+1.2$ ms^{-2}.

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):44-63

doi: 10.17816/transsyst20184444-63

5.3. EXTERNAL DYNAMIC LOAD - EARTHQUAKES

Potential earthquake dynamic loads on the Hyperloop infrastructure vary between geographic regions and they are regulated in each region by technical rules and standards. The actual civil engineering design practice is to provide sufficient strength and ductility capacities to the substructure components (columns, foundation, bearings and expansion joints) to meet the service and seismic performance requirements.

Despite better detailing and confinement in modern structures leading to enhanced damage tolerance and reduced collapse susceptibility, significant damage to this kind of infrastructure has occurred following seismic events in all the sides of the world. Such damage requires extensive repair or complete replacement of the columns and superstructure. To guarantee post-earthquake serviceability and reduce the repair costs, research efforts in recent years have been directed towards the development and implementation of innovative materials, supplemental damping and energy-dissipation mechanisms, and seismic response modification techniques for new and existing structures.

One of these seismic performance enhancement strategies, particularly effective for sites with medium to high seismic hazard or directivity effects, is seismic isolation.

The concept of seismic isolation is particularly interesting for the Hyperloop infrastructure, because of a series of potential advantages related to its specific structural characteristics. The high degree of protection given by a seismic isolation system will ensure the continued functionality and minimize the damages into a few mechanical elements that may be easily checked and replaced, if need to be.

In addition, mostly of the mass of the Hyperloop superstructure is concentrated on the tubes structure, and this part of the structure is designed to remain fully elastic under seismic input.

The base isolation technology has the following characteristics:

• Flexibility to lengthen the period of vibration of the superstructure to reduce seismic forces in the substructure;

• Energy dissipation to limit relative displacements between the superstructure above the isolator and the substructure below;

• Adequate rigidity for service loads (e.g. wind and operational accelerations) while accommodating environmental effects such as thermal expansion, creep, shrinkage and eventual prestress shortening.

The design of the isolation system should be taken in account and interact with the Hyperloop dynamics, although for the preliminary design stage, simplified lumped mass models and non-linear analysis in the time domain, using spectro-

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

compatible accelerograms, could give some direction for the choice of the optimal design.

Earthquake Early warning systems

Japan is one of the regions of the world that is highly exposed to earthquake risk. In the same time, it has a dense rail network of trains, and many of them are running at operative high-speed. To slow down or even stop the trains during an earthquake as soon as possible, they developed an early warning system based on the detection of the seismic P-waves at distant stations from the tracks. Once detected, the system sends a warning signal to the general control center that will alert the train before the S-waves arrive at the train tracks. This efficient system could be surely adopted in the Hyperloop infrastructure to enhance the safety during a strong seismic event.

5.4. EXTERNAL DYNAMIC LOAD - WIND

Generally, the wind effect depends on the geographical position of the district, its altitude from the sea level, the local topography and to some geometrical characteristics. As opposed to the wind force evaluation of any other transportation technology, the hyperloop system has the big advantage that the vehicles are not directly exposed to the wind pressure or gusts or storms or any other atmospheric phenomena. As most of the structures the wind-induced resonant vibrations might be negligible during the preliminary design stage. For the tubes structure, as well as the ausiliary and substructures, the wind responses can be determined using the procedures applicable for static loads. More detailed dynamic analysis is required during the design stage to investigate and eventually mitigate the dynamic effects of the wind.

Vortex-shedding

When a fluid flows over a slender structure, alternative vortices are shed over its sides resulting in the generation of an inconsistent force due to low pressure regions being created in the direction normal to the flow of the fluid. This systematic formation pattern of vortices is referred to as the *Von Karman vortex street*.

When the shedding frequency of the vortices (depending on *Strouhal* and wind speed) is in resonance with one of the natural frequencies of the tubes structure, large amplitude vibrations may be expected in a plane normal to the flow. The phenomenon of vortex shedding is generally significant for the lower natural frequencies of the structure, but for flexible structures having a low damping ratio, this might occur at higher frequencies as well. The vortices will be shed by the flow of wind in the downwind side and large amplitude vibrations may result if the natural frequency of tube structures is in resonance with the shedding frequency.

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):44-63
doi: 10.17816/transsyst20184444-63

The vortex shedding phenomenon generally occurs at steady wind flow conditions at a critical velocity. The periodic vibrations of the shed vortices may lock-in with the natural frequency of the structure causing high amplitude vibrations in the transversal plane to the wind flow. The oscillations generated by vortex shedding can be quite severe to cause fatigue cracks in the structures

The *Strouahl* number 0.2 is usually referred to free-air vertical element while the Hyperloop tubes are relatively close to the ground and the structural scheme is a continuous span rather than a single cylinder. A more realistic approach is recommended, which could be developed using software platforms like ANSYS CFD and imposing the boundary conditions related to the position and orientation of the tubes, both along straight line and curved one. The numerical simulations should interact with the dynamics related to the levitation and guidance system and it should be explored at different vehicle speed as well.

CONCLUSION

Musk's *Hyperloop Alpha* white paper provided an innovative spark to transportation technologies when introduced the Hyperloop. It is clearly seen that it could be considered as an evolution of the Maglev transportation system, which share with Hyperloop many technical features and advantages (and design limitations as well). Maglev is an already proven technology seen operational in high speed train systems throughout the world and more consideration should given to using it for the Hyperloop technology.

While nowadays Hyperloop is often proposed and described as the best transportation solution, with clear goals for the functionality of the system and undeniable economic advantages for the community, more thorough engineering analysis is required to assess its technical viability. In this paper the main subsystems related to the infrastructure design were broken down into its fundamental parameters and governing physical principles. These were then briefly analyzed to evaluate their effect on both their corresponding subsystem and the overall Hyperloop performance.

Although the technical aspects of the Hyperloop are quite challenging, it will be surely feasible to build an operational system. This will require a substantial amount of prototyping and design refinement. The basic indications and tentative approach concerning the design of the civil infrastructures could be used to create a more developed foundation to advance the Hyperloop work. While technical solutions will be found to ensure high performance and passenger satisfaction, it will be other aspects that have the potential to keep the Hyperloop from leaving the concept stage. Economics and community pressures will dictate the future of the Hyperloop.

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184444-63

Been involved with the civil infrastructure design of an Hyperloop system I see the possibility of one day connecting any two major cities across the world by less than a couple hour capsule ride very inspiring.

References

1. Musk E. Hyperloop Alpha – Hyperloop alpha design proposal, Space X [Internet]. [cited 2018 Jul 9]. Available from: http://www.spacex.com/sites/spacex/files/hyperloop_alpha.pdf.
2. Weinberg B. Five hundred miles an hour. *Popular Science Monthly* 1917; 90:705-708
3. Lee HW, Kim KC, Lee J. Review of Maglev Train Technologies. *IEEE Transactions on Magnetics* 42.7 (2006):1917-1925. doi: 10.1109/tmag.2006.875842
4. Ono M, Koga S, Ohtsuki H. Japan's Superconducting Maglev Train. *IEEE Instrumentation & Measurement Magazine*. 2002;5(1)9-15. doi: 10.1109/5289.988732
5. Post RF, Ryutov DD. The Inductrack: A Simpler Approach to Magnetic Levitation *IEEE Transactions on applied superconductivity*. 2000;10(1):901-904. doi: 10.1109/77.828377
6. Park C, Cheon D, Park J. Analytical Model of Fluid Flow through Closed Structures for Vacuum Tube Systems Hindawi Publishing Corp. *Mathematical Problems in Engineering*, 2015 Article ID 210727, 6 p.
7. Eisenbahn-Bundesamt, *Magnetschnellbahn Ausführungsgrundlage*, *Fahrweg Teil I–VI*, 2007
8. Janzen R. TransPod Ultra-High-Speed Tube Transportation: Dynamics of Vehicles and Infrastructure. Proceedings of the Engineering X International Conference on Structural Dynamics EURODYN, 2017.
9. Cai Y, Chen SS, Rote DM, Coffey HT. Vehicle-guideway interaction for high speed vehicles on a flexible guideway. *J. Sound Vib.*, 1994;175(5):625-646. doi: 10.1006/jsvi.1994.1350
10. Paultre P, Chaallal O, Proulx J. Bridge dynamics and dynamic amplification factors - a review of analytical and experimental findings *Can J Civ. Eng.* 1992;19:260-78. doi: 10.1139/l92-032
11. Wandg HP, Zhang K, Li J. Vibration analysis of the maglev guideway with the moving load. *Journal of Sound and Vibration*. 2007; 305(4-5):621-640. doi: 10.1016/j.jsv.2007.04.030
12. U.S. Department of Transportation Federal Railroad Administration, Safety of High Speed Magnetic Levitation Transportation System High-Speed Maglev Trains. German Safety Requirements RW MSB.
13. EN 13803-1:2010 Railway applications – Track Alignment design parameters. Part1: Plain line.
14. EN 1991-2:2003 Eurocode 1. Actions on structures. Part 2: Traffic load on Bridges.
15. EN 1991-4:2005 Eurocode 1. Part 4: Wind actions.

Information about the author:
Santangelo Andrea, Doct. of Engineering;
E-mail: contact@andreasantangelo.us

To cite this article:
Santangelo A. Hyperloop as an Evolution of Maglev. *Transportation Systems and Technology.* 2018;4(4):44-63. doi: 10.17816/transsyst20184444-63

Received: 20.10.2018. Revised: 20.10.2018. Accepted: 17.12.2018.

UDC [УДК] 338.47
DOI 10.17816/transsyst20184464-76

© I. M. Gulyi, E. S. Sivertseva
Emperor Alexander I St. Petersburg State Transport University
(St. Petersburg, Russia)

MODERN TRENDS OF TRAINING SPECIALISTS FOR INNOVATIVE DIRECTIONS OF TRANSPORT DEVELOPMENT

The aim of this paper is to reveal the features of modern transformations leading to rapid obsolescence of many professions of transport branch and emergence of new ones. The article presents forecast of emergence and formation of new competences of experts as the inevitable condition for transportation management and future transport operation.

The study rests on the Autor's curve which reflects the change of employment rate depending on qualification. The graphic-analytical and statistical research methods were used.

The problem specified is acute not only for Russia, but for other countries as well facing rapid technological paradigms change. The necessity to form new competencies for transport workers for efficient functioning of transport industry.

Transport engineering higher education institutions must launch new educational programmes.

Keywords: transport system, "supra-professional" skills, intellectual systems, profession, digital technologies.

© И. М. Гулый, Е. С. Сиверцева
Петербургский государственный университет путей сообщения Императора Александра I
(Санкт-Петербург, Россия)

СОВРЕМЕННЫЕ ТРЕНДЫ ПОДГОТОВКИ СПЕЦИАЛИСТОВ ДЛЯ ИННОВАЦИОННЫХ НАПРАВЛЕНИЙ РАЗВИТИЯ ТРАНСПОРТА

Выявить особенности современных трансформаций, которые приводят к устареванию многих профессий транспортной отрасли и появлению новых специальностей. В статье приведен прогноз появления и формирования новых компетенций специалистов как необходимое условие осуществления перевозок и управления транспортом будущего.

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

В основу исследования положена кривая Аутора, отражающая изменение занятости в зависимости от квалификации работников. Использованы графоаналитический и статистический методы исследования.

Указанная проблема весьма актуальна не только для России, но и для других стран, где происходит быстрая смена технологических циклов. Рассматривается вопрос о необходимости формирования новых компетенций работников транспорта для эффективного его функционирования.

В транспортных вузах нужно вводить новые направления обучения.

Ключевые слова: транспортная система, «надпрофессиональные» навыки, интеллектуальные системы, профессия, цифровые технологии

INTRODUCTION

The humanity of today is becoming increasingly mobile. In this regard, the role of transport branch is even more relevant, it is constantly increasing. Our travelling for both short and long distances is becoming more frequent, and we are tending to impose even more requirements to speed, safety, comfort, and economical efficiency of travelling. The intellectual systems are already replacing humanity in many ways and are becoming an integral part of transport infrastructure both in terms of traffic and transport modes operation. In Russia, ground transport provides connectivity of the vast territory, but the tempo of changes in this field has not been considerable in the past decade. However, global competitiveness will force the country to transfer to up-to-date transportation and transport operation methods and technologies [1].

MATERIALS OF RESEARCH

Logistics management is gradually passing from human to computer control. It is not only "stuffing" that gets smart, but the materials and surfaces as well. Now, adaptive roads (equipped with sensors and solar batteries), light superdurable structures and high-tech materials are being introduced. The cartographic services will be replaced by smart mainlines, which will directly update transport on the current road situation. This will enable a more efficient route planning and faster decision making.

With the number of unmanned cars increase forecast, this solution seems ideal [2, 3].

The speed of travelling is constantly increasing, allowing, for instance, railway transport to compete with planes at short distances. The world's fastest train is Japanese JR Maglev covering 580 km in one hour. There are other alternative projects as well.

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184464-76

As the age of digital transformation advances, some professions disappear. This is a natural state of things, since it is seen in any change of technology cycles: coachmen were replaced by taxi drives, postmen – by mail transfer agents. But if earlier it used to take decades or even hundreds of years for a cycle to changed, now their duration is limited to 10–15 years [4].

There are a number of peculiarities in today's tendencies of technological, social, marketing, and management-related transformations, which will cause fast-moving obsolescence of many professions, their change and spring-up of new ones. Among those peculiarities are: increasing complexity of management process systems and the necessity for high-capacity intellectual digital systems to participate more actively in decision-making processes, apart from humans; automation of operational and management-related tasks; dilution of market and competition markets, increase of life expectancy of population (Fig. 1). The factors mentioned will soon drastically change the structure of demand for some professions at job markets.

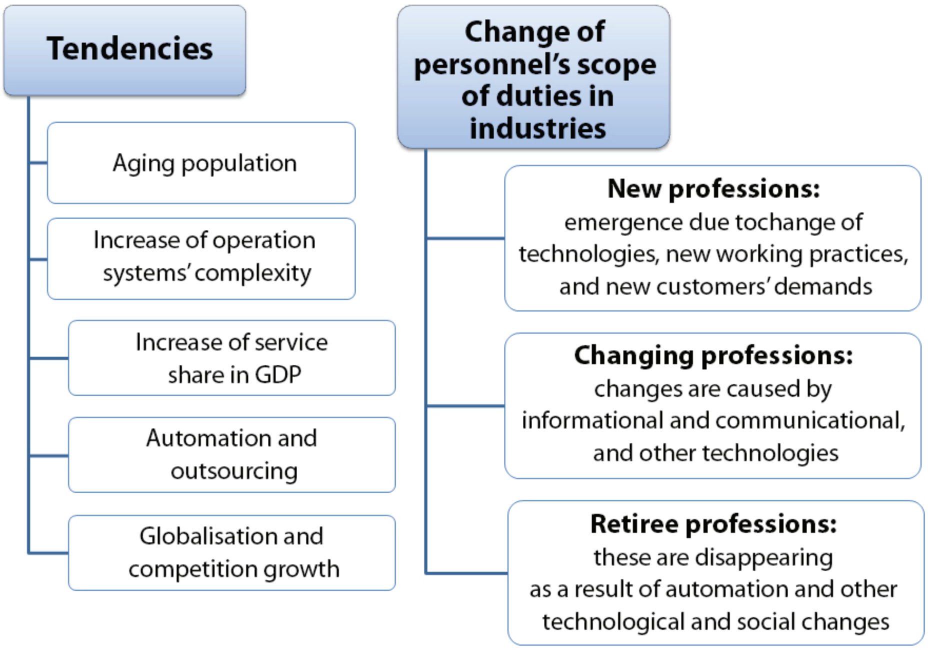


Fig. 1. Key tendencies in XXI century triggering emergence of future professions

Let us illustrate what has been mentioned above. The first example is a widespread profession of motorman. Every year unmanned control systems are improved more and more. They are expected to be first used in metro trains and freight trains. The man will participate in control only when it comes to emergency situations. By the middle of XXI century, freight train unmanned control will have become a widespread practice.

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):64-76

doi: 10.17816/transsyst20184464-76

The second example is a profession in transport service sphere, namely transport hub specialist. Currently, there are information robots which help passengers orient themselves at stations, and special machines (such as cleaning and towing machines) are gradually becoming more automated. In the future, they will be controlled remotely, therefore airports and railway stations will demand fewer service personnel.

The third example is a well-known ticket seller. Transport infrastructure is becoming more sophisticated, passenger traffic is increasing, and the requirements to safety and speed are rising. The man will find it difficult to handle these tasks soon. The automated service machines and terminals are being massively introduced, whose service can be provided via mobile applications. Human involvement will be limited to control highest level decision making when it comes to incidents and complicated situations. Therefore, the profession of a ticket seller is becoming out-of-date.

Another most significant factor of XXI century professional development is that the profession gained is not static. This means that on graduating with it, a young professional is not guaranteed a full success [6]. The most sought-after professionals are those who "absorb" the so-called "supraprofessional" skills [5], required in future professions. Among these are (Fig. 2):

− a systematic way of thinking;

− intercultural communication;

− aptitude for project management, application of project-focused approach in solving professional tasks;

− lean production practice and optimal (namely, the one with the minimal resources use) option of task solving;

− aptitude for working with robots and AI systems;

− customer-focused approach;

− multicultural and multilingual skills;

− skills for work with people and employee's integration into work with various social groups;

− skills for work in high uncertainty conditions (because of environment changes);

− creativity skills.

The supraprofessional skills are universal, since they are important for different fields of employment. Mastering these will enable an employee to increase their professional activity efficiency and pass to other fields, still being in high demand [7].

Another important tendency of the past decades cannot be omitted. Today, the highest impact of digitalisation and automation is made on blue-collar and

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):64-76
doi: 10.17816/transsyst20184464-76

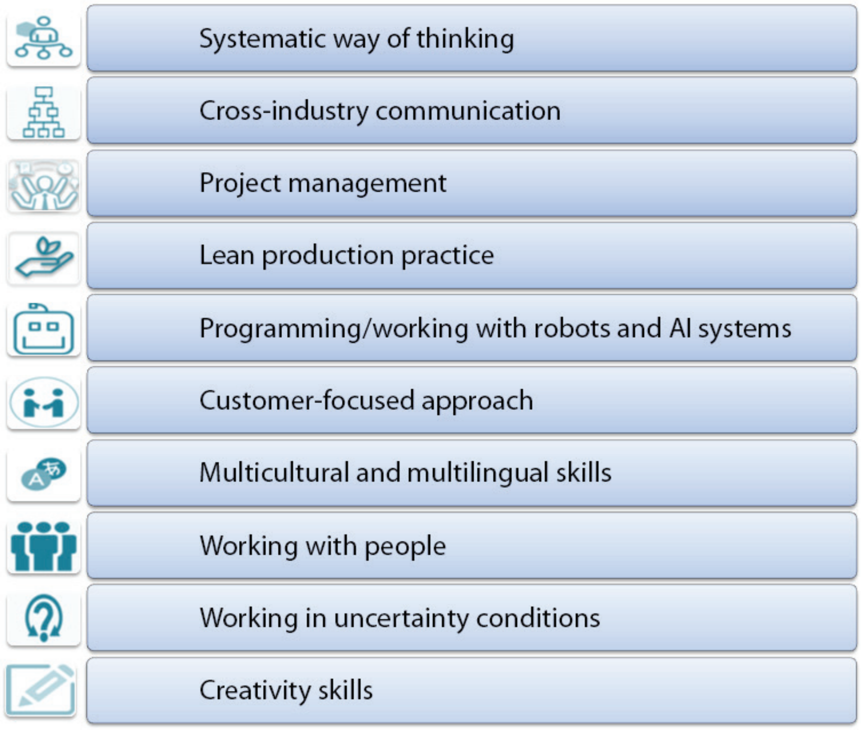


Fig. 2. Required supraprofessional skills for future professions

middle specialists. To confirm this, let us consider the Autor's curve (presented by American economist David Autor), which reflects alterations in employment rate in USA industry from 1980 until 2005, depending on an employee's qualification (Fig. 3).

It is seen that, for a period of 25 years in USA the employment degree of low and highly-qualified employees increased, and the number of middle qualification workers decreased. This was caused by widespread use of automated solutions for medium-level tasks. The automation in any industry always starts with middle qualification works, since they contain a sufficient volume of template operations which are easy to automate, and they are paid good enough to make this process attractive for business owners.

Let us pass on to description of some future professions, expected to emerge within the following decades.

The emergence of new professions will be accompanied by setting the following transport tasks:

– design and operation of transport systems (unmanned ones);
– design of automated transport control systems;
– transport safety provision;
– design of cross-logistics systems;
– design of intermodal transport hubs;

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):64-76

doi: 10.17816/transsyst20184464-76

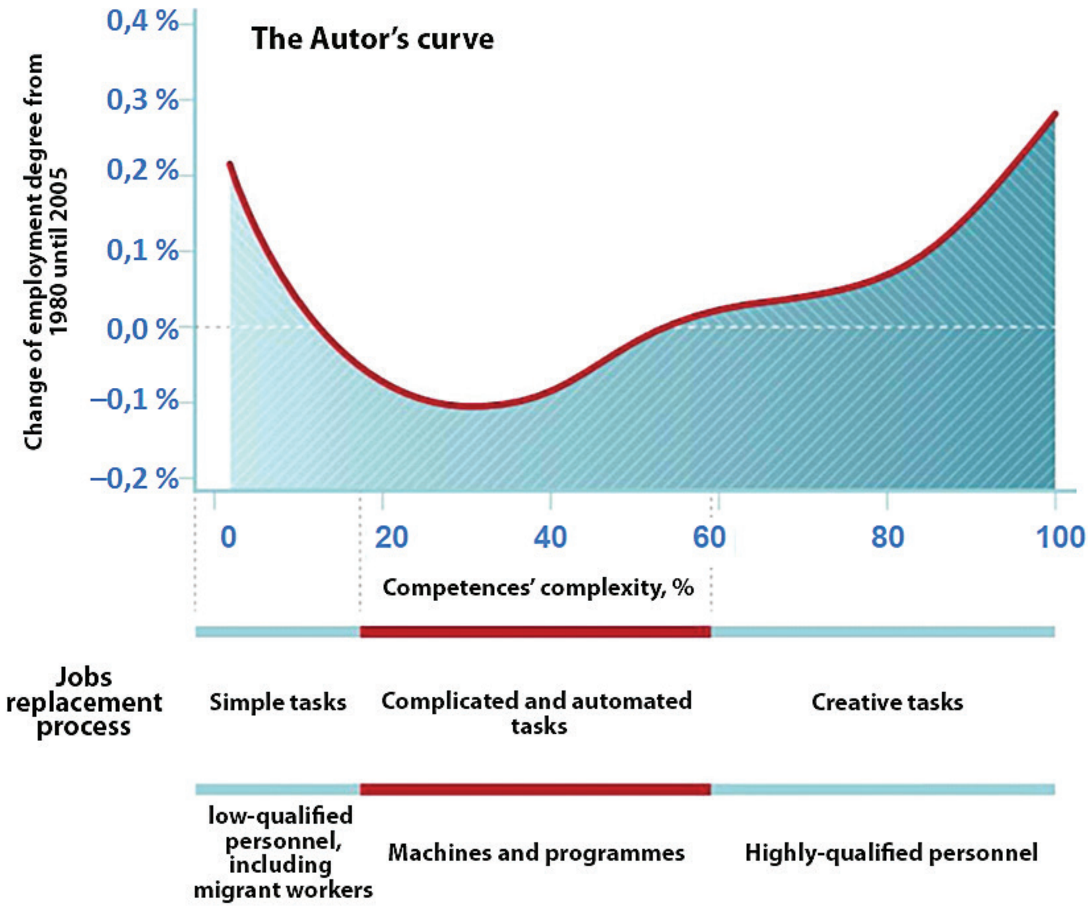


Fig. 3. The Autor's curve [5]

– design of smart roads;
– application of new materials for ground transport;
– design of HSR projects.

The digital transport transformation is expected to give rise to:

– high-speed railway transport represented as a complex in each territory [8];
– development of global freight logistics (on the basis of Radio Frequency Identification, the system now used in metro tickets);
– unmanned cars and lorries;
– smart roads with adaptive surface;
– electrical cars in cities;
– беспилотных легковых и грузовых автомобилей;
– «умных» дорог с адаптивным покрытием;
– электромобилей в городах;
– freight screening without unpacking.

What are exactly these future professions in transportation sphere?

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):64-76

doi: 10.17816/transsyst20184464-76

This is, for instance, *cross-logistics operator*, a professional engaged in selecting the best methods of freight and passenger delivery using different modes of transportation; control and adjustment of traffic throughout a multimodal network; monitoring of the throughput capacity of transportation hubs; redistribution of traffic flows in transportation networks.

Intermodal transport hub designer, a professional to be engaged in designing intermodal transportation hubs (transport modes changing system), calculating their capacity, durability, and assessing their development potential.

Intermodal transport technician, engaged in servicing technologically heterogeneous transport structure, intermodal freight and transport hubs, infrastructure, and railway stations premises.

The new profession is also considered *a high-speed railway designer*. This professional designs railway tracks, junctions and stations for high-speed travelling, considering area features and climate conditions.

Due to development of alternative types of materials and structures, *designer of composite structures for transport* will emerge. This professional will design structures (framework, liners, details) using composite materials with the set weight, durability, and wear resistance, etc.

Another much sought-after profession will be *smart road builder*, who will choose and install adaptive road surface, marks, and road signs with RFID, surveillance systems, and road state control sensors.

Due to mass automation, the Fourth Industrial Revolution, the companies will face demand for *automated transport systems operator*, who will operate robotised transport systems, configure computer programmes for robotised mechanisms and transport modes (unmanned ones in the first place).

As the digitalisation develops, the transport industry will need *smart management systems architect*, who will design software for unmanned vehicles and traffic management systems, and control smart management systems. Various solutions exist today to monitor complex shipments, though shipments are managed by people. The future will require automated traffic management systems [9].

The age that requires public security will see emergence of *transport network safety engineer*. Among his duties there will analysing and monitoring information, environmental and technological threats to transportation networks. Unlike traffic safety experts, these engineers analyze and prevent problems connected with the functioning of whole transportation networks. With the increasing speed of data transmission, demand is growing for faster riding and higher speed of transportation, which means more stringent requirements for network infrastructure and safety [10–12].

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184464-76

It is beyond any doubt that the professions mentioned will require mastering supraprofessional skills, covered earlier in this work. Fig. 4 shows as a matrix the key cross-competences to be possessed by a transport professional of the future.

	Systematic way of thinking	Inter-industry communication	Project management	Lean production practice	Programming/working with robots and AI systems	Customer-focused approach	Multicultural and multilingual skills	Working with people	Working in uncertainty conditions	Creativity skills
Automated transport systems operator	✓			✓	✓					✓
Transport network safety engineer	✓	✓	✓		✓		✓	✓	✓	
Cross-logistics operator	✓		✓	✓		✓	✓	✓	✓	
Intermodal transport hub designer	✓	✓	✓	✓	✓		✓			
Intermodal transport technician				✓		✓	✓		✓	
Smart road builder			✓	✓	✓					
Designer of composite structures for transport	✓	✓	✓	✓	✓					
High-speed railway designer	✓	✓	✓	✓	✓					
Smart management systems architect	✓	✓	✓	✓	✓					

Fig. 4. Supraprofessional skills for transport professionals of tomorrow [5]

It needs to be pointed out that JSC "Russian Railways" today are actively implementing pilot projects using new digital technologies. As an example, the following can be pointed out [13]:

– unmanned traffic control on Moscow Railway;

– unmanned operation of marshalling locomotive on October Railway;

– development and implementation of integrated automated rolling stock receiving and diagnosis station at stations – the Bataysk station of North Caucasus Railway;

– expansion of functional capabilities of complex electronic system of updating data at Moscow-Uzunovo section of Moscow Railway;

– expansion of functional capabilities of the interval traffic control system using automated locomotive signalling with data transmission by digital radio

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):64-76

doi: 10.17816/transsyst20184464-76

channel without using rail circuits at Bolshevo-Fryazino section of Moscow Railway;

− establishment of the Centre for automated monitoring of traffic parameters [13].

For successful realisation of "the Programme of Semi-High-Speed and High-Speed Railway Communication in the Russian Federation", it is obligatory to have qualified personnel of the highest level [14]. In the conditions of global digital development, JSC "RZD" should prove that it is capable of fulfilling the tasks of a national railway freight and passenger transportation operator not only now, but in the future as well, by fostering breakthrough researches [15].

For realisation of pilot projects and subsequent work, professionals are demanded that would possess all mentioned cross-competences. Emperor Alexander I St. Petersburg State Transport University is already using these competences both in education and compiling new education programmes in order to fulfill the following functions:

project and economic activity:

− ability to assess efficiency of the projects considering uncertainty factors;

− ability to form a project team and efficiently organise work in groups.

analytical activity:

− ability to analyse and use various information sources to perform economic calculations;

− ability to make forecast of major social and economic indicators of activity of a caompany, branch, region, and economy as a whole;

− ability to design varieties of decision-making solutions and justify their choice building on social and economic efficiency criteria.

informational and analytical activity:

− ability to evaluate influence of macroeconomic environment on functioning of organisations, and state and municipal governmental bodies, to identify and analyse market-based and specific risks, and analyse customers' behaviour and form demand using knowledge of economic principles of organisations' behaviour, market structure and competitive environment of the industry;

− eagerness to act in unusual situations, bear social and ethical responsibility for decisions made;

− eagerness for self-development, self-realisation, and use of creative potential;

− eagerness to lead the team in one's professional area, tolerating social, ethical, confessional, and cultural differences;

− ability to make organisational decisions;

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184464-76

− ability to independently prepare tasks and develop project decisions including uncertainty factor, develop relative methodical and normative documents as well as prepositions and activities on realisation of the designed projects and programmes, and other competences of no less importance.

CONCLUSION

Thus, emergence of new professions is not a predetermined scenario of the future, which can come with a certain degree of certainty, but a prerequisite for development and maintaining of competitiveness of transport system and national economy.

Currently in education process the institutions are governed by Federal State Educational Standard (FGOS) and must use them as the basis for methodological guidance in training specialists, considering new requirements which are constantly updated by legislation. The competences fixed in FGOS of this generation are divided into universal competences, which comprise general scientific, instrumental, general cultural, general professional, and special competences.

The use of these instruments in the process of education means planning each class in the form the required competences, which are demanded in a professional's activities. The results of mastering these competences should become: knowledge and skills to be demonstated by a person on completion of lectures, practical trainings, laboratory practices, etc. Since realisation of competences takes place during fulfillment of various kinds of activity associated with solving of theoretical and practical tasks, the structure of the competences should include (apart from standard knowledge and skills) motivational, and emotional and volitional spheres. And we must understand that the competence formed is not abstract, it should demonstrate itself in a person's behaviour in a certain situation. In order to fix and describe a competence, we need to solve a task of assessing competences. The assessment and control procedures are undertaken both at training stage and by employer, having many approaches and various viewpoints. And educational institutions undertake training in accordance with FGOS, whereas employers during hiring process assess graduates by professional standards, developed by Ministry of Labour and Social Protection of Russia, and entry questionnaires. As matter of fact, it is extremely difficult to combine different legislation requirements in training sphere and employers' eagerness to have highly professional personnel. It is exactly therefore the above-mentioned supraprofessional skills are sought-after in today's reality and are a prerequisite for development and retaining of competitiveness of transport.

Emperor Alexander I St. Petersburg State Transport University is one of the first universities in Russia to realise in its education process new training

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):64-76
doi: 10.17816/transsyst20184464-76

programmes for future transport. On completion, graduates possess knowledge, skills, and other significant competences required for promotion of innovative management on high-speed transport [14].

Библиографический список / References

1. Казанская Л.Ф., Палкина Е.С. Императивы инновационного развития транспортной системы в условиях глобализации // Экон. жел. дорог. – 2016. – № 12. – С. 52–58. [Kazanskaya LF, Palkina ES. Imperativy innovacionnogo razvitiya transportnoi systemy v usloviyakh globalizatsii. *Ekonomika zheleznykh dorog*. 2016;(12):52-58. (In Russ.)].
2. Цифровой бизнес: учебник / под науч. ред. О.В. Китовой. – М.: ИНФРА-М, 2018. – 418 с. [Kitivii OV, editor. Tsifrovoy biznes: uchebnik. Moscow, INFRA-M, 2018. (In Russ.)].
3. Казанская Л.Ф., Савицкая Н.В., Камзол П.П. Перспективы развития беспилотного транспорта в России // Бюл. результатов науч. исслед. – 2018. – № 2. – С. 18–28. [Kazanskaya LF, Savitskaya NV, Kamzol PP. Perspektivy razvitiya bespilo tnogo transporta v Rossii. *Bulletin of research results.* 2018;(2):18-28. (In Russ.)].
4. Журавлева Н.А. Цифровая экономика как основа экономики высоких скоростей // Транспортные системы и технологии – 2017. – Т. 3. – № 2. – С. 47–49. [Zhuravleva NA. Digital economy as the basic of high-speed economy. *Transportation Systems and Technology.* 2017;3(2):47-49]. doi: 10.17816/transsyst20173247-49
5. Атлас новых профессий. АНО «Агентство стратегических инициатив по разработке новых проектов». Доступно по: https://asi.ru/reports/16344. Ссылка активна на: 02.09.2018. [Atlas novykh professii. ANO "Agentstvo strategicheskikh iniciativ po razrabotke novykh projektov". Available from: https://asi.ru/reports/16344. (In Russ.) Accessed September 2, 2018.].
6. Гулый И.М., Петухов В.В. Анализ баланса спроса и предложения на рынке труда молодых специалистов // Новая экон. – новое об-во. – 2011. – № 6. – С. 72–75. [Guliy IM, Petukhov VV. Analiz sprosa i predlozheniya na rynke truda molodykh specialistov. Novaya ekonomika – novoye obschestvo. 2011;(6):72-75. (In Russ.)].
7. Казанская Л.Ф. Качество системы образования как индикатор развития транспортной системы в условиях глобализации. Сб. тр. X С.-Петерб. конгр. «Профессиональное образование, наука и инновации в XXI веке». Доступно по: https://elibrary.ru/item.asp?id=27436546. Ссылка активна на 12.11.2018.[Kazanskaya LF. Kachestvo systemy obrazovaniya kak indikator razvitiya transportnoi systemy v usloviyakh globalizatsii. (Congress proceedigs) (In Russ.) Available at: https://elibrary.ru/item.asp?id=27436546. Accessed November 12, 2018].
8. Казанская Л.Ф. Развитие высокоскоростного железнодорожного транспорта как фактор повышения конкурентоспособности национальной экономики страны // Экономика и управление в XXI веке: актуальные вопросы, достижения и инновации. Пенза: Наука и просвещение, 2017. – С. 55–63. [Kazanskaya LF. Razvitiye vysokoskorostnogo zheleznodorozhnogo transporta kak factor povysheniya konkurentosposobnosty natsionalnoi ekonomiki strany. In: Ekonomika i upravleniye v XXI veke: aktualniye voprosy, dostizheniya i innovacii: monograpiya. Penza: 2017. P. 55-63. (In Russ.)].

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

9. Давыдов С.С. Использование компетентностного подхода к обучению для обеспечения реализации стратегии развития железнодорожного транспорта // Роль образования в формировании экономической, социальной и правовой культуры. СПб, 2014. – С. 382–386. [Davydov SS. Ispolzovanie kompetentnostnogo podkhoda k obucheniu dlya obespecheniya realizatsii strategii razvitiya zhelezhnodorozhnogo transporta. *Rol obrazovaniya v formirovanii ekonomicheskoi*, *sotsialnoi i pravovoi kultury*. *Sbornik nauchnikh trudov. Government of St. Petersburg*, *Committee on Science and Higher Education.* 2014:382-386. (In Russ.)].
10. Казанская Л.Ф. Оптимизация критериев эффективного управления безопасностью движения в железнодорожной компании // Уч. зап. Межд. банк. ин-та. – 2017. – № 21. – С. 146–158. [Kazanskaya LF. Optimization of Criteria for Effective Traffic Safety Management in Railway Company. *Proceedings of the International Banking Institute*. 2017;(21):146-158. (In Russ.)].
11. Казанская Л.Ф., Ризакулов Ш.Ш., Артимович В.М. Направления повышения экономической эффективности управления движением в железнодорожной компании // Уч. зап. Межд. банк. ин-та. – 2017. – № 22. – С. 115–129. [Kazanskaya LF, Rizakulov ShSh, Artimovich VM. Directions of Increase of Economic Efficiency of Traffic Safety Management in Railway Companies. *Proceedings of the International Banking Institute*. 2017;(22):115-129 (In Russ.)].
12. Казанская Л.Ф., Ризакулов Ш.Ш. Построение системы управления в железнодорожной компании с учетом экономических факторов // Бюл. результатов науч. исслед. – 2017. – № 2. – С. 15–25. [Kazanskaya LF, Rizakulov ShSh. Postroyeniye systemy upravleniya v zheleznodorozhnoi kompanii s uchetom ekonomicheskikh factorov. *Bulletin of research results*. 2017;(2):15-25. (In Russ.)].
13. Российские железные дороги (ОАО): офиц. сайт. Доступно по: http://www.rzd.ru. Ссылка активна на 02.09.2018. [Russian railways OJSC: Available from: http://www.rzd.ru. (In Russ.) Accessed September 02, 2018].
14. Сиверцева Е.С. Новые направления подготовки кадров для решения современных задач развития сети ВСМ в РФ // Матер. межд. науч.-практ. конф. «Августин Бетанкур: от традиций к будущему инженерного образования». СПб, 2018. – С. 193–196. Доступно по: https://elibrary.ru/item.asp?id=34854822. Ссылка активна на 12.11.2018. [Sivertceva ES. Novye napravleniya podgotovki kadrov dlya resheniya sovremennykh zadach razvitiya seti VSM v RF. (Conference proceedings) Materialy mezhdunarodnoi nauchno-prakticheskoi konferentsii "Avgustin Betankur ot traditsii k budushchemu inzhenernogo obrazovaniia"; 2018 Feb 01-02; St. Petersburg; 2018. P. 193-196. (In Russ.) Available from: https://elibrary.ru/item.asp?id=34854822. (In Russ.) Accessed November 12, 2018.].
15. Давыдов С.С. Экономические аспекты цифровой железной дороги // Транспортные системы и технол. – 2017. – Т. 3. – № 2. – С. 39–41. [Davydov SS. Ekonomic features of digital railway. *Transportation Systems and Technology.* 2017;3(2):39-41]. doi: 10.17816/transsyst20173239-41

Information about authors:
Ilia M. Gulyi, Candidate of Economic Science (PhD)
eLibrary SPIN: 1788-1967, ORCID 0000-0001-8676-1561
E-mail: ilya.guliy@mail.ru

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

Elena S. Sivertseva,
eLibrary SPIN:2917-1809; ORCID 0000-0002-2087-0260
E-mail: sivlen@mail.ru

Сведения об авторах:
Гулый Илья Михайлович, кандидат экономических наук
eLibrary SPIN: 1788-1967, ORCID 0000-0001-8676-1561;
E-mail: ilya.guliy@mail.ru

Сиверцева Елена Сергеевна,
eLibrary SPIN:2917-1809; ORCID 0000-0002-2087-0260;
E-mail: sivlen@mail.ru

To cite this article:
Gulyi IM, Sivertseva ES. Modern Trends of Training Specialists for Innovative Directions of Transport Development. *Transportation Systems and Technology.* 2018;4(4):64-76. doi: 10.17816/transsyst20184464-76

Цитировать:
Гулый И.М., Сиверцева Е.С. Современные тренды подготовки специалистов для инновационных направлений развития транспорта // Транспортные системы и технологии. – 2018. – Т. 4. – № 4. – С. 64–76. doi: 10.17816/transsyst20184464-76

Received: 31.10.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

DOI 10.17816/transsyst20184477-111

© A. M. G. Jacob[1], N. M. V. Monteiro[2]
[1] ISEP – Polytechnic School of Engineering
[2] bimTEC – Building Information Modeling Consultants
(Porto, Portugal)

A NEW CONCEPT OF SUPERELEVATION IN MAGNETIC LEVITATION – PRODYNAMIC

Background: The topic of Magnetic Levitation systems, in terms of land mass transport, have created high expectations compared to aviation and also to the high speed railway industry. This new concept comes to revolutionize the terrestrial mass transport, in both the speeds and the subject of friction. Magnetic levitation solves the issue of attrition between material contact and as such may also be an opportunity to solve the question of constant physical superelevation.

Aim: Precisely that point of superelevation coupled with magnetic levitation, eliminating the rigid physical structures to laterally lift the vehicle in a curve. Current magnetic levitation systems do not address this issue of dynamic superelevation. It's exposed an improvement technology which is a theoretical possibility of a track through a new magnetic line can apply necessary rotation to the vehicle in curve and adjust its rotation according to the speed that vehicle moves.

Methods: In order to make this system to work it is suggested the introduction of a magnetic field in the new line, which will allow the vehicle to rotate in curves and will negate the need of the conventional static superelevation.

This study appeared as a result of an investigation of a master's thesis in civil engineering at ISEP, where the participants created the concept of dynamic superelevation in the context of magnetic levitation. The project was applied to the reformulation of an existing railway network. The study base of this model resulted from a broad survey of current magnetic levitation systems. Then came the idea of creating a third dynamic magnetic field to operate the curved superelevation.

Results: The result of the study was the creation of a new «monorail» system of simple and geometrically constant structure. The new line has the advantage of providing a simple and constant geometry, facilitating the manufacture, assembly and thus making it much more economical compared to the current systems. The cross-section allows the vehicle to fit perfectly and with the creation of rotating magnetic fields, the vehicle can be turned to both sides, at the required inclination, according the speed. With this new concept called ProDynamic, the geometry design in plan is totally independent of the speed practiced by the vehicle, where it can travel in curve at different speeds, but with the same lateral no-compensated acceleration, without detriment of passenger comfort.

Conclusion: Combining existing systems with this new concept, it is possible to create a total freedom in curves and superelevation, which will provide a maximum comfort and significant construction savings. There is therefore no longer a problem of deficiency or excess cant, as currently exists on railways. The advantage in the ProDynamic system is that it is possible to greatly reduce or even eliminate the lateral no-compensated acceleration.

Keywords: Levitation, Maglev, Train, High Speed Railway, Electromagnetism, Superelevation, Curve.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

INTRODUCTION

Magnetic levitation represents the first major advanced propulsion revolution since the creation of the internal combustion engine, in which this system offers the possibility of traveling faster, more economically and safer. The world is currently changing, the first electric vehicles are already emerging, and with these vehicles new ways of approaching transport, not only for road users, but also for railways. The railway is a known system and has evolved considerably but has limitations and drawbacks such as the lack of intrinsic friction of the wheel-rail contact system. The magnetic levitation system has the potential to transform and give rail transport a new dynamic by evolving high-speed lines in another dimension, shortening distances and being able to compete with aviation transport.

The first line of magnetic commercial levitation was recently implemented in Shanghai with the German Transrapid system, the Japanese government plans to have its magnetic levitation line operational in the next few years. In addition to these projects already in progress there are also plans for various countries. The scope of this article is a hypothetical approach to magnetic levitation systems, where it can be translated by the theoretical possibility of the vehicle turning on itself in a curve, thus not having to apply a static cant to the curved rail. This paper presents two different systems, which guarantee a higher productivity and have the objective of making the application of curved rails faster and faster. The curved application is equal to the application of the straight-line system. The only difference is that in curve there is a new magnetic field that induces the rotation of the vehicle. The rotation is performed by the track that rotates the vehicle in a corner at the angle of the speed of the vehicle, thus achieving a better relation between speed, rotation and comfort of the passengers.

This article describes the two new magnetic levitation systems proposed and idealized in the ISEP, which consist of the capacity of the vehicles to rotate on themselves, thus not necessitating the existence of superelevation in the rail. The characteristics of the track and the vehicle are also described, as well as the verification of the curve layout, the maximum possible slope for each system and the minimum curve radius to be implemented to guarantee the comfort of the passengers due to the non-compensated centrifugal force or even eliminate it.

HISTORICAL CONTEXT OF MASSIVE LAND TRANSPORT

The first rails to be created were rudimentary and go back to the early eighteenth century, where the first carriages were pulled by horses. With the

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184477-111

industrial revolution, the development of railways has undergone a profound transformation.

Nowadays there are railway systems that can reach speeds more than 400 km/h, being systems that have evolved from the conventional railway line and have undergone some considerable adaptations to be able to move at high speeds.

Railways were also one of the great catalysts of the various disciplines of Civil Engineering, because due to the existence of natural and other geological obstacles, it forced the development of bridges, tunnels and other infrastructures. It also helped the growth of cities and their development as they were linked by a more efficient means of transport.

George Stephenson also built Locomotion 1, also known as The Rocket. It was the first locomotive with tubular boiler and with its own system of passenger transport called experimental. He was able to transport or pull loads weighing between 55 and 75 t at a maximum speed of approximately 16 km/h. The following image shows a photograph of Locomotion 1 [2].

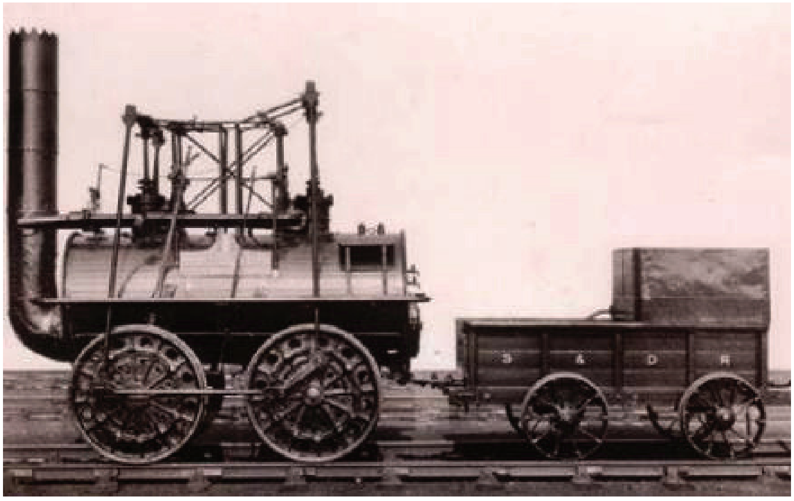


Fig. 1. Locomotion 1 "The Rocket" [1]

A new mode of transport was thus created as an exceptional growth rate that spread throughout the world and revolutionized the entire mass transport system.

The high-speed lines had their most significant development in the 1950s after World War II. On October 4, 1964, the first passenger high speed line was inaugurated by Japan Railway Shinkansen. The system implemented was able to reach the top speed of 210 km/h and brought a return on investment in 7 years, having this train became known as a "bullet" train. The first minimum radius of the high-speed lines was 2500 m, which was found to be too small and then increased to a minimum radius of 4500 m, in a very short time. However, for speeds in the

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):77-111
doi: 10.17816/transsyst20184477-111

order of 300 km/h, again these spokes were too low. A minimum radius of 7000 m and preferably a minimum radius of 10 000 m was then considered. The initial tunnel section was 62 m^2 and for the new "bullet" trains the current minimum section is about 100 m^2.

Fig. 2. Highspeed Train JP Shinkansen S-0 (*Source:* ナダテ *Nadate*, *2008*)

At the beginning of the new 21st century, JR Shinkansen began to develop the third generation of high-speed railway lines, with the purpose of increasing the speed of operation to 350 km/h. Thus they conceived the E5 in a program called Fastech360 capable of reaching speeds of 320 km/h as can be seen in next image [4].

Fig. 3. Highspeed Train JR Shinkansen E5 (*Source: Nanashinodensyaku*, *2011*)

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

The second country that successfully developed the high-speed railway was France. It built the first high-speed line from Paris to Lyon using TGV-PSE technology in 1981, 17 years after Japan. According to the classification, these trains were able to reach speeds upper than 280 km/h, belonging to the technology of first generation. Second-generation trains appeared 20 years later, on the TGV-Mediterranée line, from Valence to Marseille, with an upgraded infrastructure. In 2007, the new TGV-EST high-speed line from Paris to Strasbourg was completed. Both lines were able to provide better conditions for the movement of the train and the maximum speed of operation of the TGV-Mediterranée and TGV-EST, thus increasing up to 320 km/h, with France reaching the speed of 300 km/h trains of the first generation. The French TGV also had the highest operating speed of the second generation, 320 km/h, which is the world record by 2008. In the third generation of high-speed, France realized that the centralized power system they used to the first generation and the second generation was not suitable for speeds above 350 km/h. Therefore, they adopted the existing technology in Japan with the distributed power system, designing their third-generation train, the AGV360, with the fastest train in the world, reaching a speed of 574.8 km/h on April 3, 2007.

However, the operating speeds of these systems are around 300 km/h for track maintenance, such as ballast, crossbars and anchorages, as well as track wear. That is, at this moment, the speed limitation in the railway is around 320 km/h, due to safety and especially maintenance/wear, taking into account that this system has permanent physical contact between two materials.

To overcome this major problem of wear/safety, a new system emerges that can be considered a fourth-generation system reaching operating speeds of over 430 km/h. This new system uses magnetic levitation to move and levitate on the rails, and which is now in commercial use in Shanghai in China, proving to be a success and promising for the future.

Aviation can be the most competitive means of transport, for distances greater than 1500 km, when compared to high-speed railway. However, with

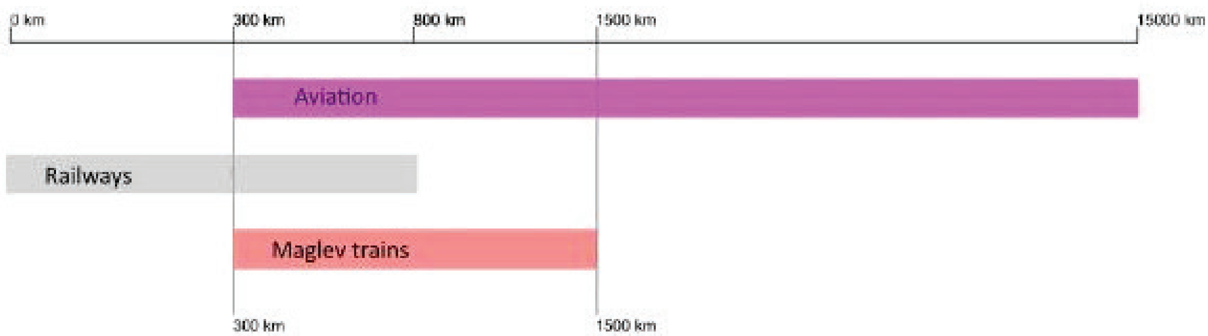


Fig. 4. Comparison of means of transport taking into account the economic factor

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

magnetic levitation, for speeds between 450 and 600 km/h, it could be a competitive option to aviation, up to distances of 2000 km. In conclusive terms, there is a very competitive space between high-speed railway and aviation, which can serve very well magnetic levitation, between 300 km and 1500 km.

HISTORICAL REFERENCES OF MAGNETIC LEVITATION

Maglev levitation uses magnetic forces to lift, orient and propel vehicles, using both attractive and repulsive forces. At the beginning of the 20th century, Emile Bachelet designed a magnetic suspension that used repulsion forces generated by alternating current. This concept of Bachelet was impracticable for the time because the amount of energy of the conventional conductors was insufficient. It was only in the 1960s when superconducting magnets emerged that it became possible to develop this technology. In the early 1920s, the work of Hermann Kemper in Germany pioneered a Maglev using attraction, called attractive-mode maglev. Kemper explored this concept during the 1930s and in the 1940s established a basic design to implement his Maglev system, having published an article in 1953.

In 1963, scientists James R. Powell and Gordan T. Danby patented the first Maglev system using superconductivity, a system based on the work of Emile Bachelet, overcoming the energy limitations that underlie this technology. In 1966, they introduced their concept of Maglev using superconductors in the vehicle and coils on the sides of the rails. This technology was then followed by the system used in the Japanese Maglev.

Another important work using Maglev technology was carried out in the United States of America in the early 1970s and refers to the development of ROMAG (people-mover demonstration vehicle) by Rohr Corporation. This system was normally driven by electromagnets that generate attractive forces between the vehicle and ferromagnetic material in the rail, a system designated by magnetic suspension system (EMS). Unlike EDS, the EMS is statically unstable, a control system that varies the currents in the electromagnets to maintain clearances between the vehicle and the lane.

The unit of measure of the International system that measures magnetic flux density is the Tesla, and thus was instituted in honor of Nikola Tesla at the *Conférence Générale des Poids et Mesures*, Paris in 1960. Nicola Tesla was an inventor in the field of mechanical engineering and electrotechnology and the creator of the alternating current that exists today in all the electrical infrastructure.

Magnetic levitation is defined as the suspended state of a body in space at some distance from the surface. To achieve this state of suspension, magnetic forces that compensate for the force of gravity are used. The magnetic field exerts

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):77-111
doi: 10.17816/transsyst20184477-111

a force strong enough to levitate and stabilize the body at a certain position relative to the surface.

In March 1912, the engineer and inventor Emile Bachelet was able to register a patent called “Levitated Transmitting Apparatus”, showing the New York public a model of a Maglev train, as can be seen in next figure.

One of the first applications of magnetic levitation was developed by Gene Covert and his MIT colleagues who created the magnetic suspension and balance system.

Maglev technology was first proposed by Emile Bachelet. A few years later, Werner Kemper proposed a type of magnetically levitated train. He obtained the patent for the magnetic levitation train on August 14, 1934 [11]. The evolution of his patent resulted in the creation of the magnetic levitation system currently used on Transrapid.

Another Maglev system with commercial use is the HSST (High Speed Surface Transportation) system, is the Japanese system that in 2005 started its commercial use called Linimo. It is an urban system with a maximum speed of 100 km/h. It is identical to the system used in Transrapid, using the attractive forces to move in the line, distinguishing itself from the Transrapid by the maximum speed that each vehicle can reach and by the differences that exist in the linear motors [13].

The development of magnetic levitation technology under the “railway” lines had different evolutions that led to different solutions of magnetic levitation.

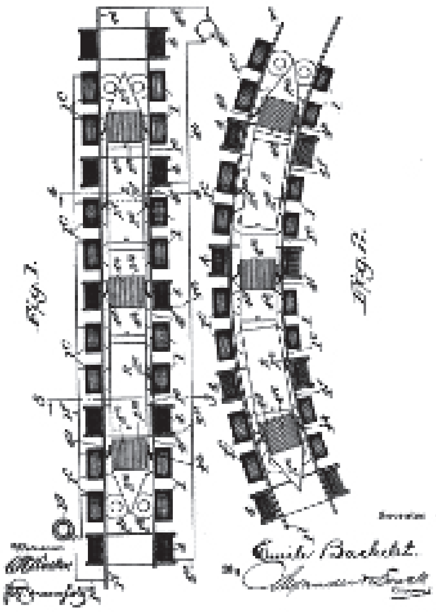


Fig. 5. Emile Bachelet system patent image [11]

Fig. 6. Construction of Transrapid infrastructure in Shanghai [12]

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

Fig. 7. Urban Maglev system Linimo [13]

Different types of magnetic levitation technologies have been achieved, with three technologies currently under development and some already in commercial use, such as the German Transrapid. Systems currently under development are EDS, EMS and INDUCTRACK.

The designation EMS comes from Electromagnetic Suspension, being the system used in Transrapid. It concerns the forces of magnetic attraction for levitation. This system uses electromagnets that are controlled electronically and individually. This type of levitation is by nature unstable and requires an effective control system with great precision to keep the Maglev train suspended.

The EDS system stands for Electrodynamic Suspension and is used by the Japanese in the JR SCMAGLEV (Japan Railway). It refers to the magnetic repulsion that consists of the use of superconductive coils that create repulsive forces propelling the vehicle. The coils are located inside the train that create a strong magnetic field in connection with the ferromagnetic bars on the rails that levitate the vehicle.

The INDUCTRAK system is the latest magnetic levitation technology. It does not use superconducting magnets or electromagnets, but permanent magnets at ambient temperature, like ordinary but more powerful magnets. These magnets produce an oscillating magnetic field and, consequently, levitate the vehicle. The main advantage of Inductrack technology over the others is that, because it is an induction activated repulsive force system, it is stable and control circuits are almost unnecessary to achieve stability.

In the 1970s, the Germans and Japanese began to develop their versions of Maglev technology. The Japanese, supported by the Japanese National Railway

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184477-111

Fig. 8. ROMAG Maglev [10]

(JNR), have expanded the development of their Maglev technology. By 1972, they had already built their model, having in 1974 their large-scale runway.

In 1970, in Germany there were already some prototype vehicles operating under the German government's jurisdiction, these being the first versions of the current Transrapid [10].

In 2003, the first commercial line with the Maglev Transrapid system with 30.5 km length is finally opened in Shanghai taking the time of 7 min 22 s.

MAGNETIC LEVITATION SYSTEMS

Magnetic levitation trains have several advantages compared to the conventional rail system because it is a system where there is no contact with the rail, so there is no friction between materials without physical wear.

There are already several studies showing that magnetic levitation systems produce less noise (about 85 % less) compared to high-speed railway systems.

They are also able to overcome greater longitudinal inclinations compared to the railway system (about 10 % inclination up to 12 %), while on the railway the maximum is about 2.5 % (commonly characterized by 25 %).

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

Levitation systems achieve high speeds over a shorter distance when compared to high-speed railway systems. Magnetic levitation vehicles can achieve better acceleration and braking performance over shorter distances than the high-speed rail, about 1/5 of the stroke length.

The magnetic levitation system is more secure compared to high-speed railway systems because it is almost impossible to «derail» due to the way the vehicle is gripped and envelops the rail.

Magnetic levitation lines have a considerably reduced operating cost compared to rail lines around 60 % less, due to the low energy consumption of the system, to relatively low wear. However, construction costs are more expensive for Transrapid by around 60 % compared to ICE [3, 14].

The vehicles of the conventional rail system transmit their weight to the rail through the axles, these being punctual loads and very high. The Maglev transmits a uniformly distributed load to the «rail», which results in less punctual efforts. In addition, it should be noted that the Maglev vehicle is considerably lighter than the conventional rail vehicle because it has no wheels or engines, less metal mass. It can be said that for the construction of an infrastructure where a vehicle with Maglev technology circulates, this structure will be slimmer and more economical.

The tunnel sections required for the Maglev system may be smaller compared to the existing sections in the rail system, ensuring economy and speed of construction.

The minimum radii of the curves for the Maglev system are smaller, thus translating a more efficient layout and less area of land to be expropriated [15].

Thus, it can be stated that although the Maglev system is about 60 % more expensive in implementation, this being the only unfavorable aspect of this technology, all other aspects are great advantages for the Maglev system. Electric consumption and the emission of greenhouse gases are intrinsically linked, and this system guarantees a reduced electric consumption compared to the current rail system, also guaranteeing greater energy and environmental sustainability in this area of transport.

EMS SYSTEM

The EMS system results in the culmination of an arduous and concentrated research in Germany over fifty years of a technology that originated in the United States of America. It is an extremely sophisticated and secure electronic integral control system [5]. The next image represents the Transrapid system already in commercial use.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Fig. 9. EMS technology used in Transrapid
(*Source: Siemens AG Transportation Systems*, *2005*)

This system emerged in the 1970s when Transrapid's German trains used the pulling forces between electromagnets and ferromagnetic bars that are controlled individually and electronically and levitate the vehicle. These electromagnets are in the vehicle and the ferromagnetic bars of the rails. The next image demonstrates a scheme of the levitation system used in Transrapid.

The vehicle has a grip-shaped bracket that involves the lateral rail where the electromagnets are located and these pull forces on the ferromagnetic supports that are located under the rails ensuring lift and levitation of the vehicle. Laterally there is a set of electromagnets that serve as a lateral guide, which has the function of controlling the transverse movements of the vehicle on the rail, thus ensuring

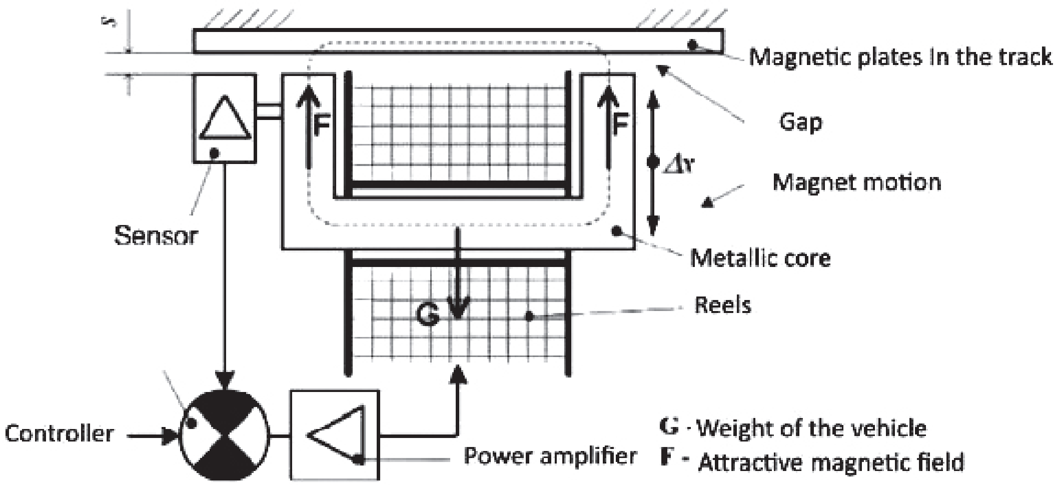


Fig. 10. Principle of Levitation EMS [3]

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

that the vehicle is centered in the track while traveling. The distance between the sides of the vehicle and the rails on the sides is 10 mm, and this is controlled electronically, while the distance between the rail and the bottom of the vehicle distance is 150 mm, which makes it possible to go over small objects or small layers of snow [5]. The nest figure shows a representation of the Transrapid system.

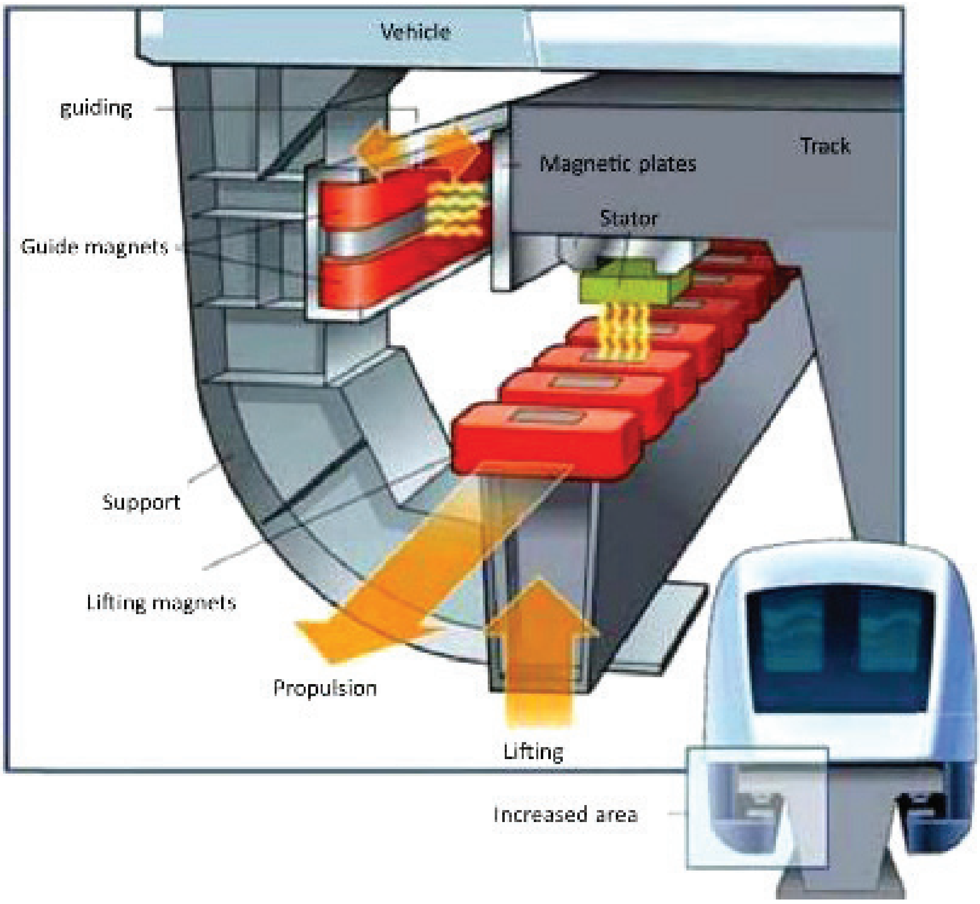


Fig. 11. EMS system used in Transrapid [6]

The propulsion system used is the synchronized linear stator motor, which is used for the propulsion and braking of the vehicle. This motor is also referred to as LMS – linear motor stator. This motor thus creates a magnetic field, which when interacting as the support magnets in the vehicle arm create forces of attraction impelling the movement of the vehicle. The magnetic field is achieved by induction of a three-phase alternating current, the speed of the vehicle is controlled by the frequency of that same alternating current of the linear motor. Braking the vehicle is achieved by changing the direction of the magnetic field, there being no physical contact between the two sides of the engine. The linear long stator motor installed in the rails is divided into sections, these being fed by the electric current only

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

when the vehicle is in the section in question. To do this, substations with different powers are required according to the track layout, since they can be traced that require considerable braking and large accelerations of the propulsion system, a situation that requires a greater power of the electric network, compared to the traces of the track in which the journey is constant.

Shown in the next figure is a diagram of how the chain moves and feeds the vehicle along the rails. It is verified that there is power for each section of rail.

The EDS (Electrodynamic Suspension) system is used in the Japanese Maglev, it uses magnetic repulsion as opposed to the EMS system, this system uses superconducting coils that give rise to repulsive magnetic forces causing the vehicle to move. The vehicle needs wheels, because at low speeds the vehicle can not reach levitation, which can only be achieved after the vehicle reaches a speed of more than 120 km/h [6].

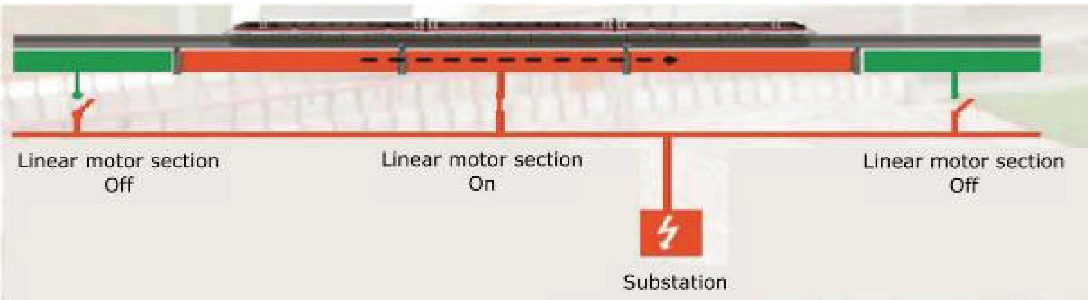


Fig. 12. Linear motor sections on track [7]

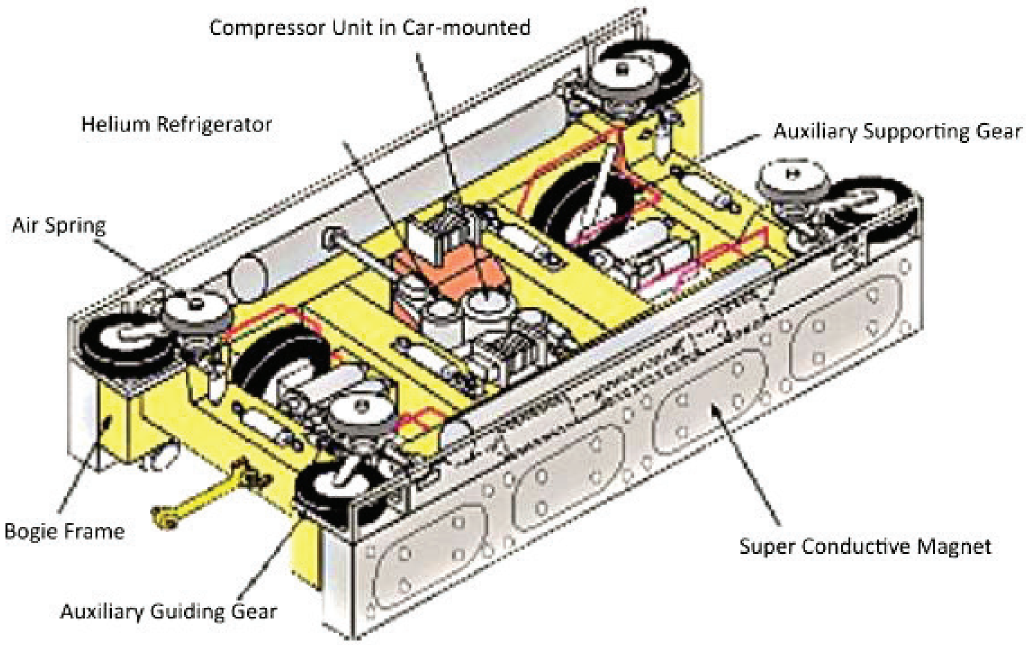


Fig. 13. MXL01 bogie system (*Source: Odec.ca*, *HBLee*, *2007*)

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

The EDS is based on the repulsive forces of lorentz, resulting from the interaction of the superconducting coils in motion with the existing coils aluminum rails. The next figure shows the MLX01 system of the Japanese magnetic levitation system in the Yamanashi test line.

Fig. 14. EDS technology used in the JR-Maglev MLX01 Japanese System
(*Source: Central Japan Railway Company – Yamanashi Maglev Test Line*, *2000*)

The interaction between the superconducting coils in the vehicle and the coils on the rail creates a strong magnetic field that is induced by the superconducting coils of the vehicle, which causes the coils on the rails to undergo polarity inversion, creating repulsive forces that levitate the vehicle. The coils on the rails are passive, non-superconducting, and have an "8" configuration, which causes the current induced by the coils in the vehicle to cause a simultaneous force that pulls the vehicle upward and pushes it down.

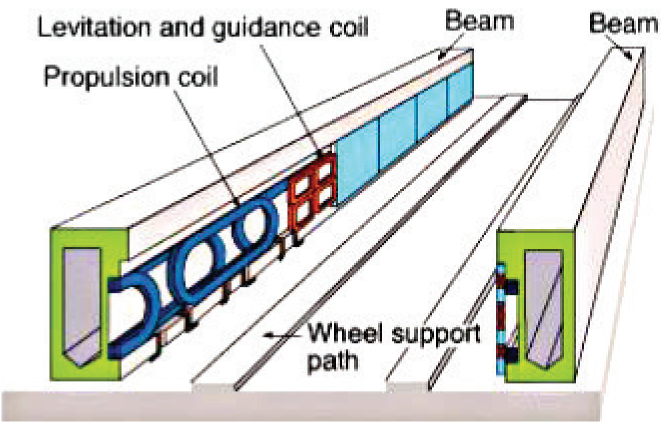


Fig. 15. Schematic of the rail used in JR-Maglev MLX01 [6]

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

The EDS system used in the JR-Maglev MLX01 uses two types of coils that have different functions on the sides of the rails. They have the function of guiding and propelling the vehicle on the track and in addition to these reels, the rail has a support for the wheels, which the MLX0 uses when traveling at speeds below 120 km/h, as shown in next figure [6, 8].

The propulsion coils located on the sides of the rails are fed by a three-phase electric substation, creating the polarity variation that will give rise to the magnetic field that drives the vehicle when they come into contact with the superconductors in the vehicle. The movement of the vehicle is carried out by alternating polarity in the lateral coils of the rails, as can be seen in next figure. The lateral coils on the left and right side of the rail alternates the polarity, thus provoking forces of attraction or repulsion forces, in the superconductors on the side of the vehicle, impelling the movement [6, 8].

Inductrack was developed in the 1990s by Dr. Richard Post at Lawrence Livermore National Laboratory in California. The system uses conventional magnets in Halbach Array, that is, Halbach arrangement, and to achieve levitation, these conventional magnets are arranged in a certain way creating a very specific magnetic field known as the Halbach arrangement. These thus create levitation,

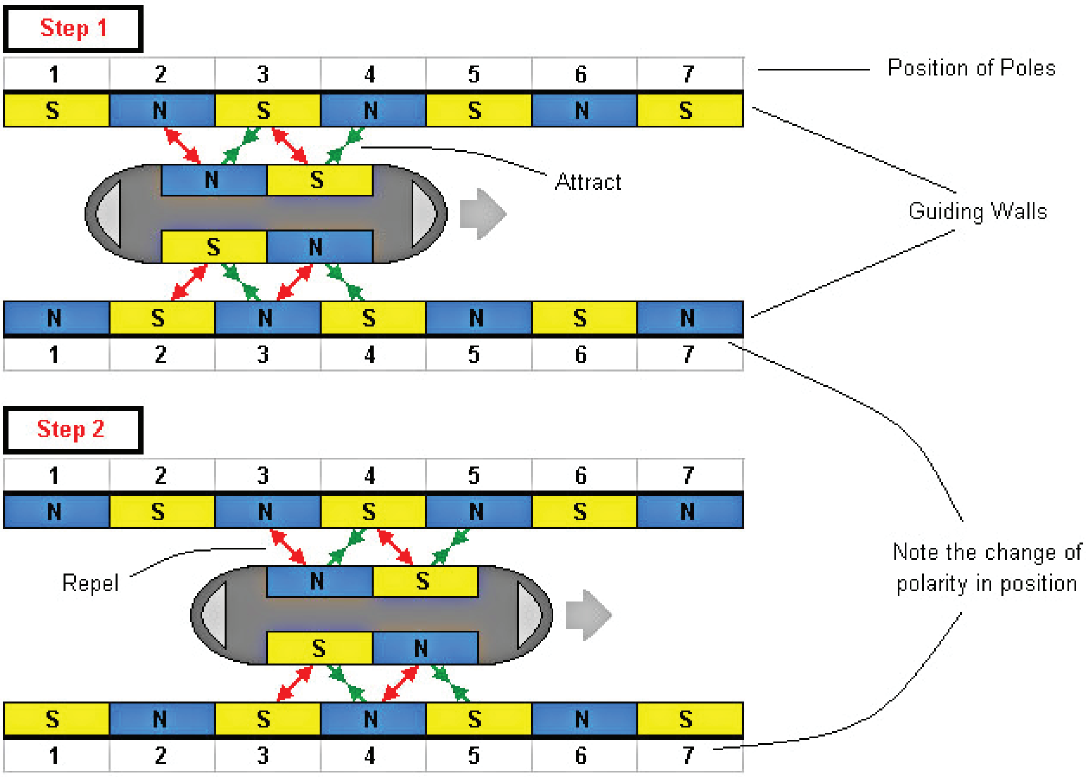


Fig. 16. Diagram of operation of the EDS System and how to change the polarity (*Source: Fiyaz Ahmed, 2009*)

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

unlike the other Maglev technologies used by the Japanese in the EDS and by the Germans in the EMS, which rely on sophisticated sensors and cryogenic refrigeration systems, to ensure levitation and movement of the vehicle on the rails. In addition, the magnets are composed of a new material comprising a neodymium-ferro-boron alloy, which generates a higher magnetic field.

The main piece of technology is the Halbach Arrangement, which is what defines the Inductrack system and distinguishes it from other competing Maglev technologies. The Halbach Arrangement guarantees some benefits that include increased safety and efficiency and reduced cost. This system was developed in the 1980s by physicist Klaus Halbach, which consists of a set of conventional magnets placed in a series of repetitions and with specific orientations that create a strong magnetic field. The following image illustrates how the magnetic field lines override the magnetic field above and at the same time create a strong magnetic field beneath the magnets. The Halbach Arrangement induces an electric current in the levitation circuits consisting of Litz wires thus levitating vehicle.

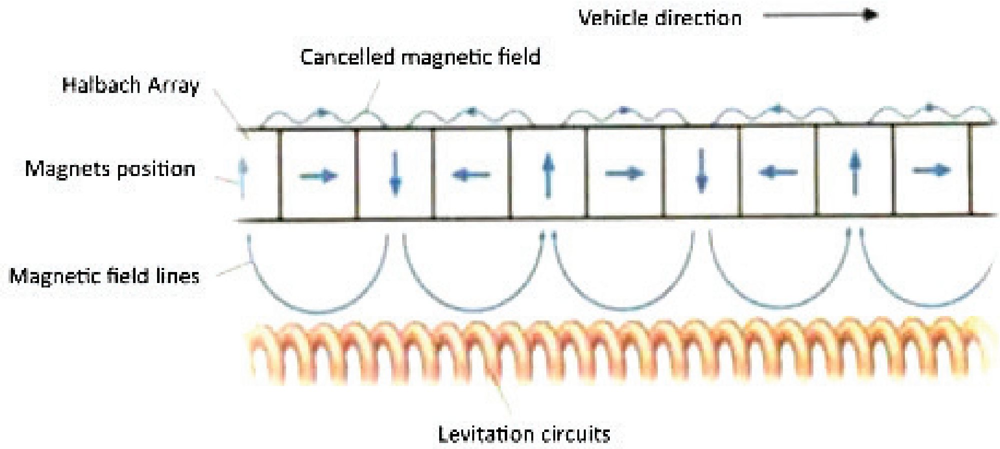


Fig. 17. Schematic of the magnetic field formed by the Halbach Array [16]

In this system there is still no comercial prototype built on a real scale because it is a recent system, but the experiences with this technology reveal many potentialities. In the next figure you can check the test vehicle that was built [16].

This vehicle with the Inductrack system when it is built will require four Halbach Arrangements, over a series of levitation circuits consisting of Litz wires. Two of the Halbach Arrays are positioned down over the circuits if they have the levitation function while the other two Halbach Arrays are positioned sideways in relation to the circuits to balance the vehicle to maintain it, as it can be seen in next image [16].

The effects of the Halbach Arrangement were substantiated by extensive tests done by Dr. Richard Post, the inventor of Inductrack, which tried to test their initial calculations, which suggested that the Halbach Arrays could levitate loads

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):77-111
doi: 10.17816/transsyst20184477-111

Fig. 18. Inductrack experimental vehicle [9]

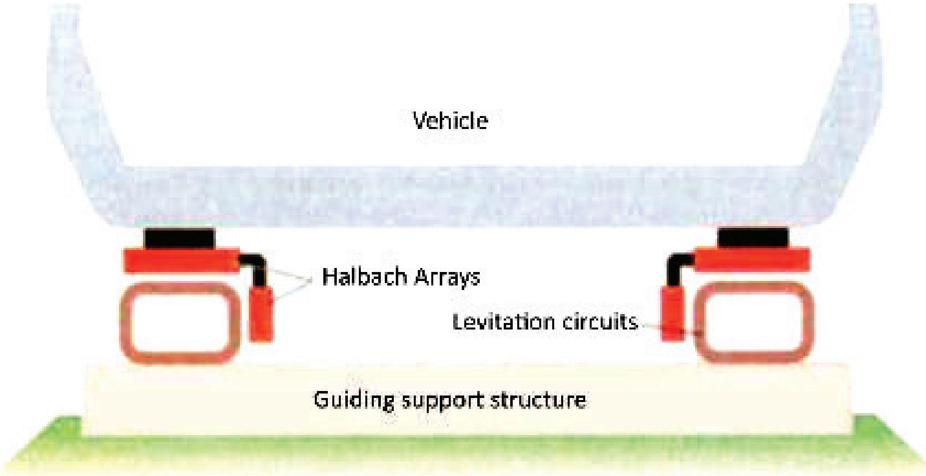


Fig. 19. Representative scheme of a possible vehicle with the Inductrack system [16]

weighing up to fifty times the weight of the magnets. To test this hypothesis, the scientific team built a scale model and launched it at a speed of about 35.4 km/h. The model proved to be stable and the lifting force proved to be that verified in the theory [16].

COMPARISON BETWEEN DIFFERENT TECHNOLOGIES EMS, EDS, INDUCTRACK

Currently there are three known Maglev systems, the electrodynamic suspension system (EDS), the Electromagnetic Suspension System (EMS) and Inductrack. Each of the three systems has different characteristics and very specific characteristics. While EDS and EMS use only the interaction of magnets and

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

superconductors, the Inductrack uses coils in rails underneath vehicle, however the three suspension systems work under the same principle of magnetic levitation. The following image demonstrates the three existing levitation systems.

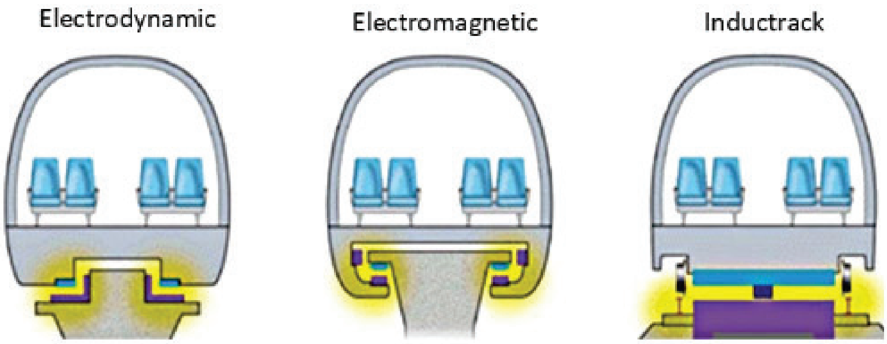


Fig. 20. Comparison systems between Magnetic Levitation Systems
(*Source: Maglev Trains A Look into Economic Concessions*, *Binyam Abeye*, *2011*)

The EMS system used in Transrapid has the following advantages:

– The magnetic fields of the system inside and outside the vehicle are smaller than in the EDS system;

– It is a commercially available technology that can reach high speeds, about 500 km/h;

– No auxiliary wheels or secondary propulsion system needed;

– The configuration of the vehicle in the form of grabs (locks) makes it almost impossible to derail the vehicle;

– The noise is due only to the displacement of the mass of air caused by the locomotion of the vehicle.

The disadvantages of the EMS System are:

– The gap between the vehicle and the guide rail must be constantly monitored and corrected by computer systems to avoid collision due to the unstable nature of electromagnetic attraction and possible irregularities in the rail;

– More vibration problems may occur.

The EDS system used by MXL01 has the following advantages:

– Superconducting magnets in the vehicle allow high speeds of around 600 km/h;

– Ability to carry heavier loads;

– Successful operations with the use of high-temperature superconductors on your liquid helium cooled magnets.

The disadvantages of the EDS System are:

– Intense magnetic fields due to superconductors on board the vehicle can endanger passengers with pacemakers or even damage magnetic data storage devices such as hard drives and credit cards;

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

– The vehicle needs auxiliary wheels when driving at low speeds;

– Cost per km system still considered very high;

– There is a considerable cost and inconvenience of having to keep refrigerated superconducting magnets at 5 Kelvin at –268.15 degrees Celsius.

The advantages of the Inductrack System are:

– Uses permanent magnets and does not use superconducting magnets;

– No need for sensors to control levitation;

– It does not give a strong magnetic field to passengers.

The disadvantages of the EDS System are:

– It is a recent system, there is no real-scale experimental line, so it can not be ascertained whether it will be effective compared to the other two magnetic levitation systems.

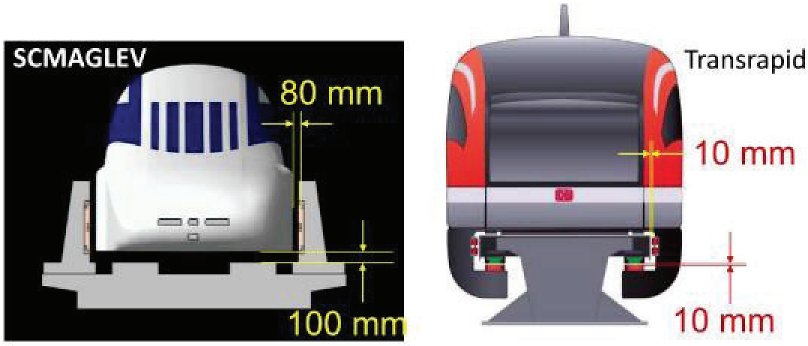


Fig. 21. Comparative distances between SCMAGLEV and Transrapid (*Source: Central Japan Railway Company*, *Yoshiyuki Kasai*, *2012*)

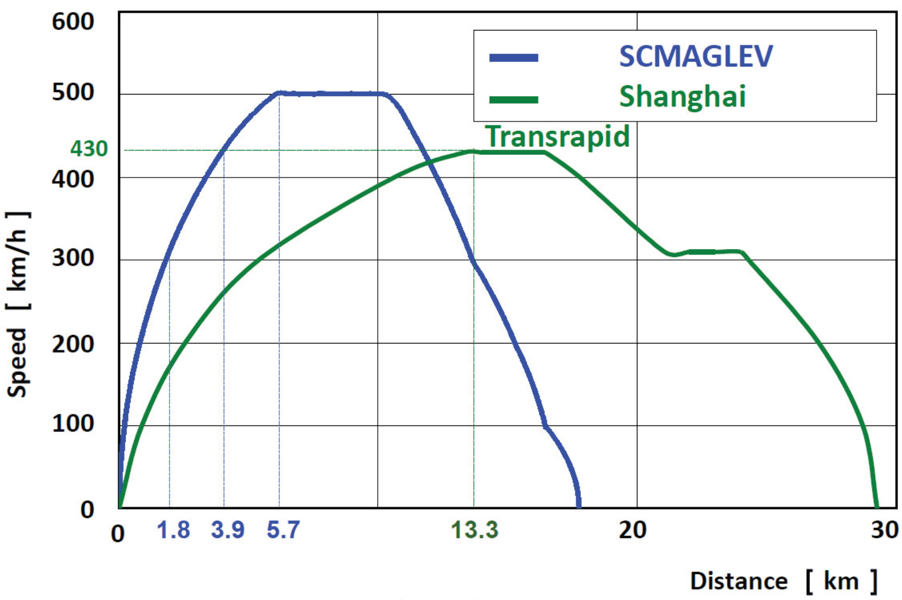


Fig. 22. Speed and acceleration performance (*Source: Central Japan Railway Company*, *Yoshiyuki Kasai*, *2012*)

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

The following image illustrates the differences between the Transrapid and SCMAGLEV relative to the distances of the vehicle to the rail.

The following image shows the differences that exist in the maximum speed between the Transrapid system and SCMAGLEV, as well as the distance that each system takes to reach the maximum speed and the distance that it takes to stop.

NEW PROPOSED SYSTEM (PRODYNAMIC)

The objective in this article is to present a possible evolution to the EMS system. As already mentioned, both the conventional railway system and the high-speed railway network present physical limitations that are intrinsic to the wheel-rail contact system, among others, the lack of friction and the costs of maintenance.

The proposed system is very similar to the existing magnetic levitation systems, the existing Transrapid system and the Japanese SCMaglev system.

This presented system was conceived by an ISEP team (teachers and students) and could be registered as a new/different approach to existing magnetic levitation systems.

The following proposal is an improvement which consists of a theoretical possibility that the rail can achieve through magnetism, apply a rotation to the required vehicle in a curve and adjust that rotation to the speed at which it travels. This system represents a new concept, an evolution and putting into practice has several advantages. The main advantage is that the construction of the rail is uniform and does not require static superelevation or cant, making the manufacture and installation of the rail much more economical.

In order for this system to work, it is suggested that a further magnetic field be introduced on the track, in addition to the propellers and guidance, which is to rotate the vehicle in a curve and to replace the superelevation of the conventional rail. This rotation in addition to the existing advantages in the construction process, also has the advantage of the vehicle adjusting the rotation according to the speed at which it travels, ensuring the best comfort for the passengers. The proposed system has, as with other magnetic levitation systems, lateral guiding forces, lift forces, propulsion forces, but also rotational forces that are only required in a curve. These magnetic forces are arranged on the rail which interact with the magnets in the vehicle as can be seen in the following figure.

The following image shows a longitudinal diagram of the rail and how it can induce rotation through a magnetic field. The rail is segmented to induce a different rotation in each section according to the speed that the vehicle is traveling in a curve.

Therefore, the construction of the rail becomes much simpler in its development in curve and achieves a reduction in the costs of execution and

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184477-111

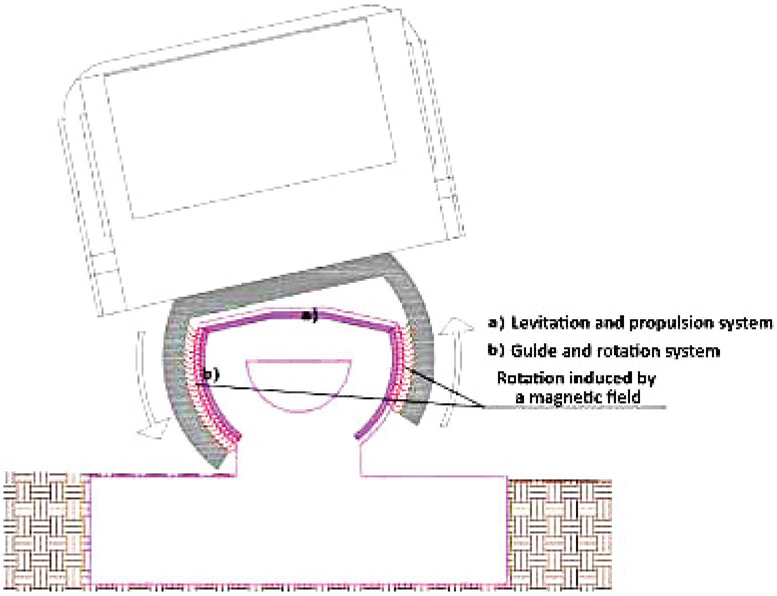


Fig. 23. Rotation scheme of the vehicle induced by a magnetic field

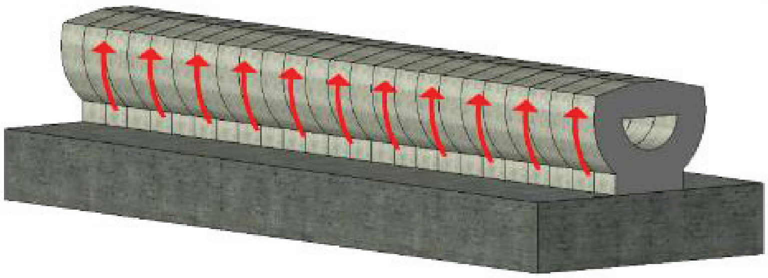


Fig. 24. Longitudinal scheme of the rail and the induced magnetic field, to generate the rotation

design, thus making more feasible the implementation of the magnetic system. For this system two hypothetical types of magnetic levitation are presented which theoretically are possible to conceive and represent an evolution to the systems currently in use and in tests. The following image shows one of the possible systems to be proposed, now called System 1.

The following image shows the other system to be proposed as system 2. The systems proposed here are distinct and are an evolutionary variant of current magnetic levitation systems.

Systems 1 and 2 are distinct in the form of the rail and in the shape of the base of the vehicle. The system 1 has a «claw» that surrounds the rail, while in system 2 the rail engages the vehicle as can be seen in the image. However, both systems use an identical levitation system. The technology proposed for the vehicle to turn in a curve is identical for both systems, so there is no need to superelevate in either of the two proposed systems. This is achieved in the construction of this

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

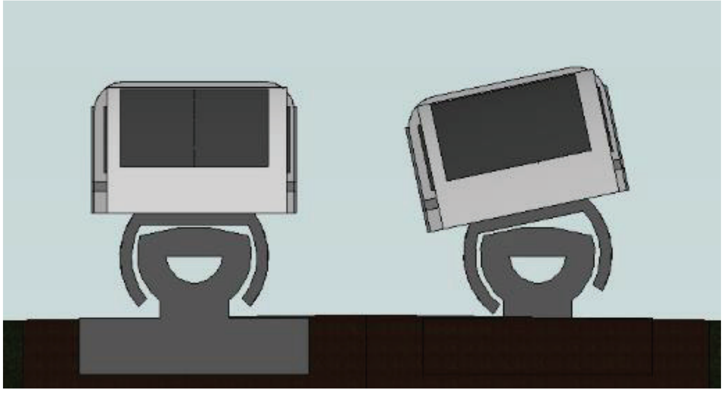


Fig. 25. Alternative magnetic levitation system 1 proposed

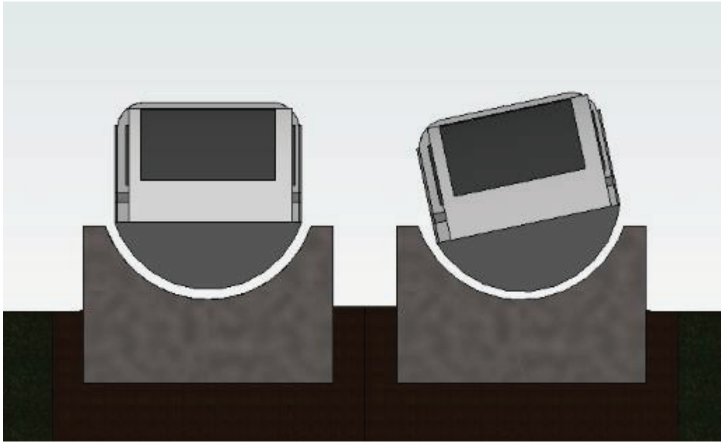


Fig. 26. Alternative magnetic levitation system 2 proposed

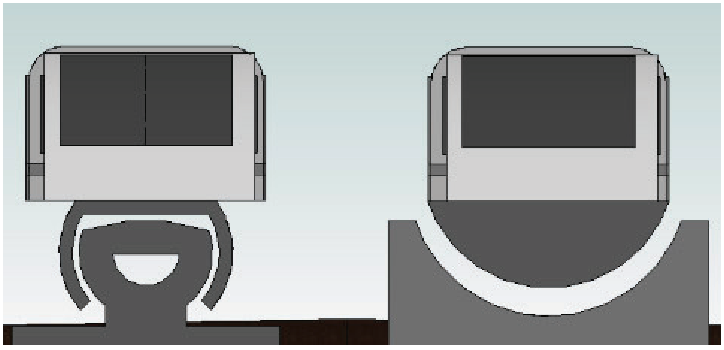


Fig. 27. ProDynamic system 1 and system 2

type of system, a productivity continues in both straight and curved, in addition the system guarantees in curve the best relation between the rotation and the speed to which it moves, guaranteeing the best possible adaptive comfort for passengers.

In the following image also it is verified that the upper part of the vehicle is equal in both systems, changing only the lower part, being able to have interoperability of infrastructure.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

SYSTEM 1 – PRODYNAMIC

System 1 results in part from a variation of the existing system in the German Transrapid. This system also has a form of grip that fits on the rail, such as Transrapid.

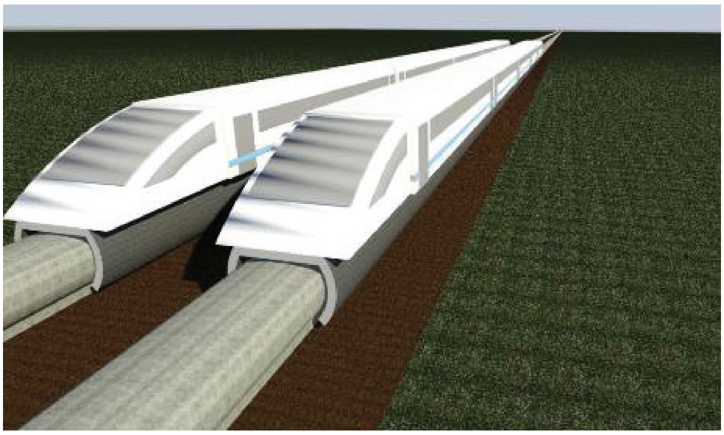


Fig. 28. Virtual image ProDynamic system 1 proposed

In the following image we can verify the similarities between the two systems, but the great difference between them consists in its curve layout, in which the proposed system does not need static superelevation. This system can rotate on the rail and apply the angle that it needs according to the speed while travelling, ensuring a greater comfort to the passengers and facilitating the constructive process with respect to the construction of the curved rail. The proposed system adapts to the speed, looking for the ideal rotation position.

The differences are essentially related to the rail and to the way the vehicle moves on the track. In the following image we can verify the constructive characteristics of the rail of this system in its longitudinal development.

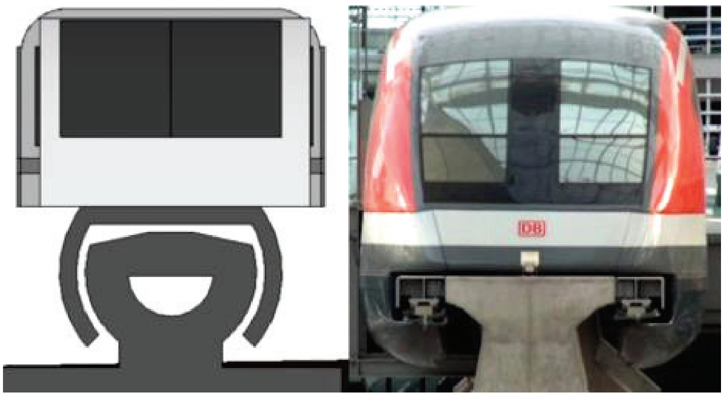


Fig. 29. Comparison between the proposed system 1 (ProDynamic) and the Transrapid system

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

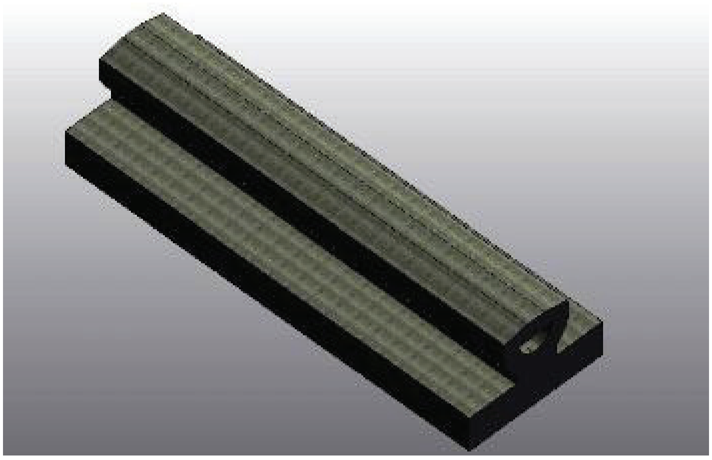


Fig. 30. Path to be used in system 1 proposed

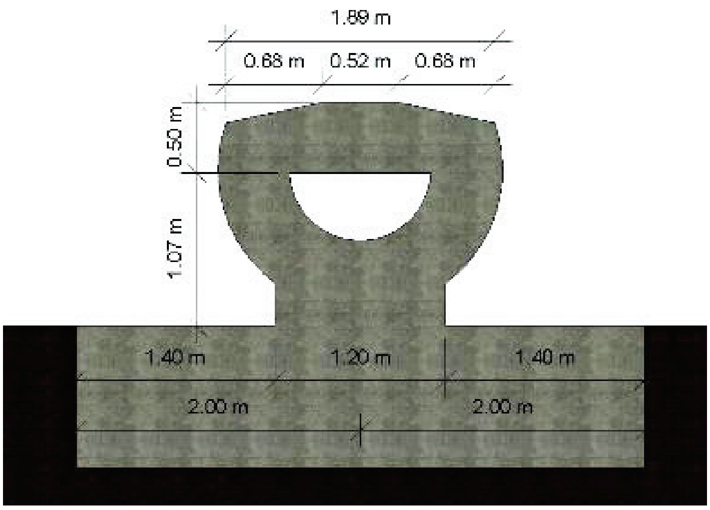


Fig. 31. Cross section of the proposed system 1 rail

The rail configuration has a cylindrical base that allows the vehicle to roll over the rail. This configuration assumes that it will be possible, through the induction of another magnetic field, to cause the vehicle to rotate on the track. With this suggestion there is a need for a third magnetic force that applies a necessary force to the vehicle so that it rotates the necessary one according to the speed in which it moves in curve, diminishing the effect of the discomfort due to the centrifugal acceleration. In addition, this magnetic field also requires constant computer control so that this rotation remains within the safety limits. The following figure shows a cross section of the rail of this system and its possible dimensions.

The vehicle has dimensions like those of the Transrapid, where they only differ in the lower area of the vehicle where it interacts with the rail.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

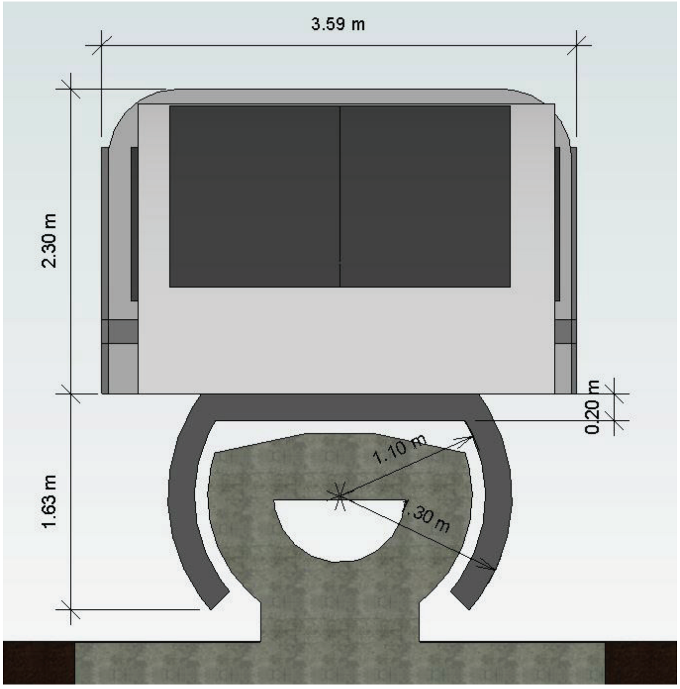


Fig. 32. Transversal perspective of the system 1 vehicle

Shown in next figure is a longitudinal perspective view of the vehicle of system 1 and its dimensions. The vehicle is composed of carriages of 15 m length, or in the case of the compositions of the extremities these are about 20 m in length.

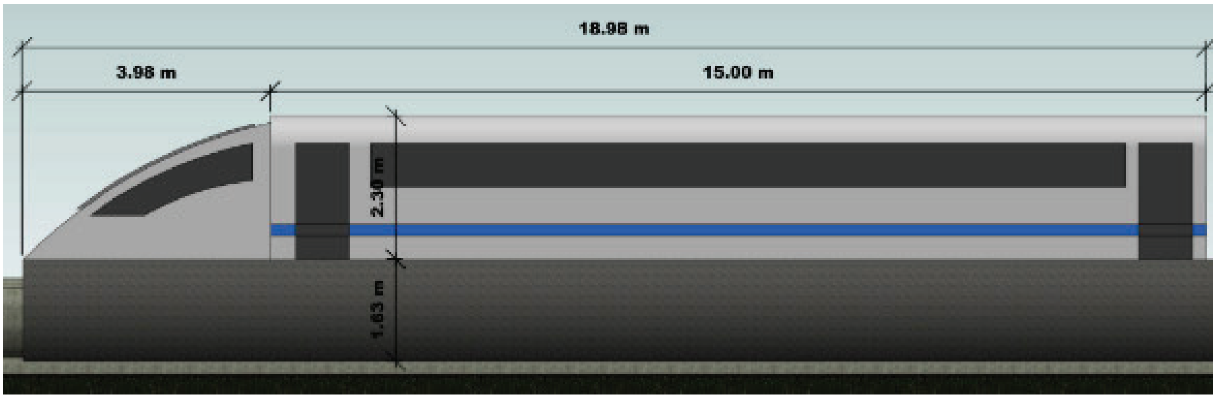


Fig. 33. Longitudinal perspective of the vehicle of the system 1

The configuration of the rail has characteristics that allow the vehicle to turn on the curved rail, with no static cant. In the following image it can see how the vehicle rolls on the rail at a maximum angle of 12º, but may be higher depending on the geometry defined for the claws and base support.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

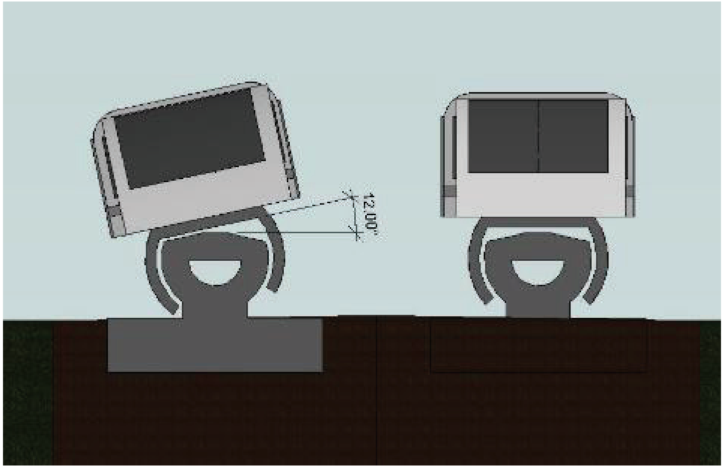


Fig. 34. Rotation of the vehicle in system 1 proposed

For the moment, this system has a maximum configuration of 12º and manages to guarantee an optimum relation between the speed at which the vehicle moves and the necessary rotation for that speed, always maintaining the ideal comfort for the passengers. The comfort of the passengers depends on the speed at which the vehicle is traveling, the radius of the curve and the inclination of the vehicle. To minimize the effect of centrifugal acceleration it is necessary that there is an ideal relationship between these three factors. The acceleration can be quantified by the simple following expression:

$$a_c = \frac{v^2}{R}, \tag{1}$$

where:

$$a_c - \text{centrifugal aceleration} (\text{m/s}^2)$$

$$v - \text{ velocity } (\text{m/s})$$

$$R - \text{ radius of the curve} (\text{m})$$

The centrifugal acceleration for rail has register values for passenger comfort up to a maximum of 1.5 m/s^2. Above this value, passengers begin to feel some discomfort. For the calculation of the centrifugal acceleration it was considered the condition of comfort limit conditioning for the passengers, the high speed and in curve. This analysis consists of moving the vehicle to an operating speed of 450 km/h with a minimum radius of curvature of 4400 m. In the following expression the value of a_c can be verified:

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184477-111

$$a_c = \frac{\left(\frac{(450 \times 1000)}{3600}\right)^2}{4400} = 3{,}551\ \mathrm{m/s^2} \quad (2)$$

It should be noted, however, that to obtain the correct comfort value for passengers, the calculation of unbalanced acceleration is used, which consists of subtracting the component from the centrifugal acceleration with the acceleration component due to the weight of the vehicle. These acceleration components are schematically shown in the following figure.

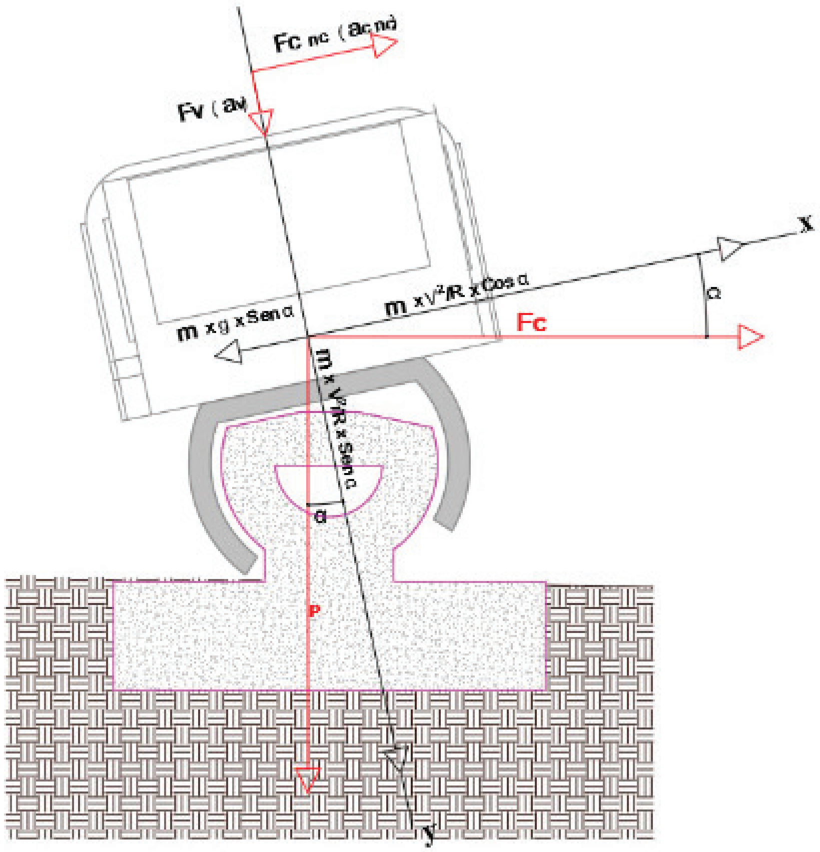


Fig. 35. Schematic of the forces acting (acceletarion directions) on the vehicle

The calculation of the acceleration component due to the weight of the vehicle for the situation depicted in the image above is obtained by expression (3).

$$g \times \sin(\alpha) = 9{,}8 \times \sin(12°) \rightarrow 2{,}037\ \mathrm{m/s^2} \quad (3)$$

The calculation of the centrifugal acceleration component for the situation represented at an angle of 12° is obtained by expression (4).

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

According to the result obtained, it possible to calculate the component of the centrifugal acceleration for the situation in analysis as can be verified in expression (4).

$$\frac{v^2}{R} \times \cos\alpha = 3.551 \times \cos(12°) \rightarrow 3.474 \text{ m/s}^2 \quad (4)$$

Using the values of expression (3) and expression (4) of the situation under analysis one obtains the unbalanced acceleration as can be seen in the next expression (5).

$$acnc = 3.474 - 2.037 \rightarrow 1.437\ m/s^2 \quad (5)$$

Thus, a value of 1.437 m/s², which is within the comfort values for passengers, was obtained up to 1.5 m/s². In the following figure for an operating speed of 450 km/h, limiting the vehicle's rotation to 12°, only comfort values with radii above 4 300 m are achieved for unbalanced lateral acceleration.

The following image shows the possible inclination (rotation) for the operating speeds and the unbalanced acceleration for each speed considering a radius of 4440 m. It is verified that all the values of the lateral unbalanced acceleration are within the comfort parameters. The acceleration depends on the

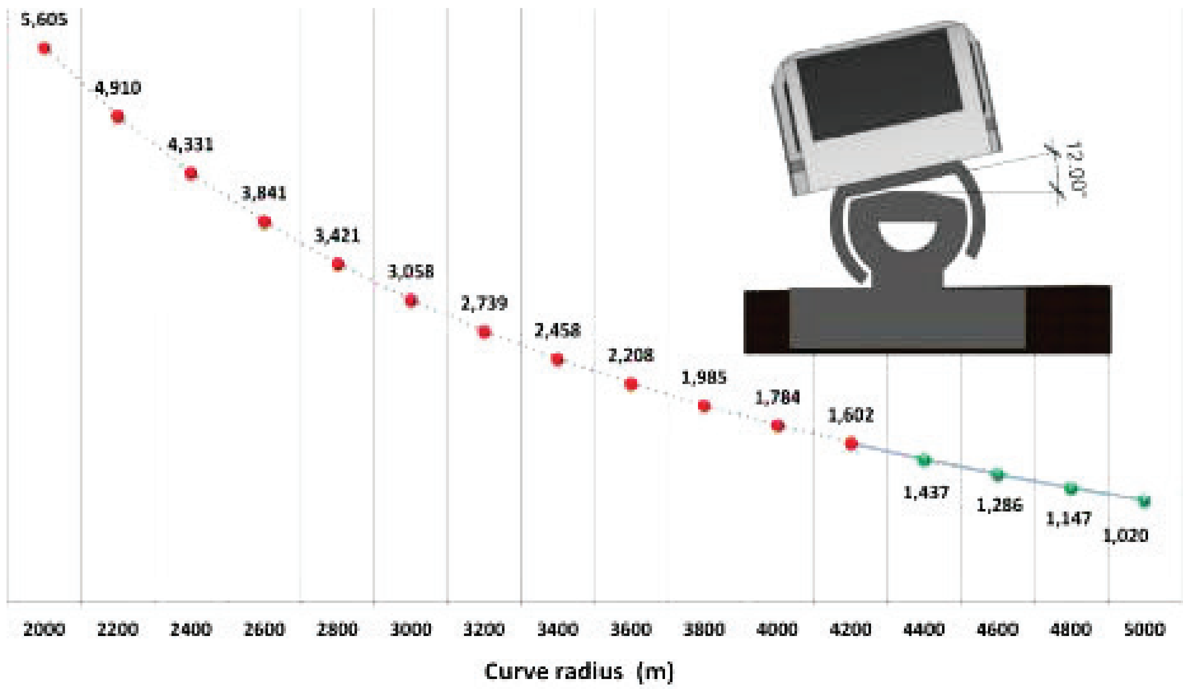
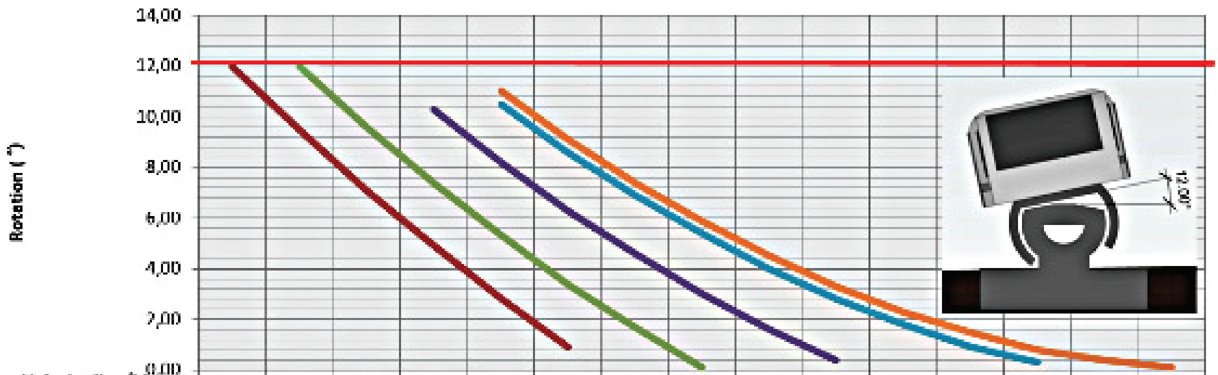


Fig. 36. Uncompensated acceleration for a speed of 450 km/h with 12° inclination versus several curve radius

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111



Velocity (km/h)	450	420	390	360	330	300	270	240	210	180	150	120	90	60	30
acn = 1,44 m/s^2	12,00	9,50	7,10	4,90	2,80	0,90									
acn = 1,00 m/s^2		12,00	9,60	7,40	5,30	3,40	1,70	0,10							
acn = 0,50 m/s^2				10,30	8,20	6,30	4,60	3,00	1,60	0,40					
acn = 0,10 m/s^2					10,50	8,60	6,90	5,40	4,00	2,80	1,80	0,90	0,30		
acn = 0,01 m/s^2					11,00	9,10	7,40	5,90	4,50	3,30	2,30	1,50	0,80	0,40	0,10

Superelevation

Fig. 37. Possible inclinaton (rotation) for operating speeds considering a constant radius of 4400 m

speed and therefore these values can always be adjusted in a curve, according the inclination and the comfort values admissible for the acceleration.

In this way, it is understood that this system guarantees a good relation between the degree of inclination, operational speed and comfort of passengers, guaranteeing a simplicity in the construction especially in a curve where this system does not have any type of superelevation in curve. The great advantage is that the work of rail construction is constant, either in a curve or straight, reducing construction costs significantly.

SYSTEM 2 – PRODYNAMIC

System two results from a variation of the existing system in the Japanese MXL01.

This system has a circular shape identical to the “U” shape that fits over the rail, such as SCMaglev. In the following image the differences between the two systems can be identified.

As in system 1, system 2 differs from the SCMaglev system due to the rail and the way the vehicle is driven over the track. This system allows, such as the system 1, that the vehicle turn on itself in a curve and does not require the existence of cant in the rail. This situation as in the system 1 involves the introduction of a magnetic force which rotates the vehicle in a curve according to the speed at which it travels.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

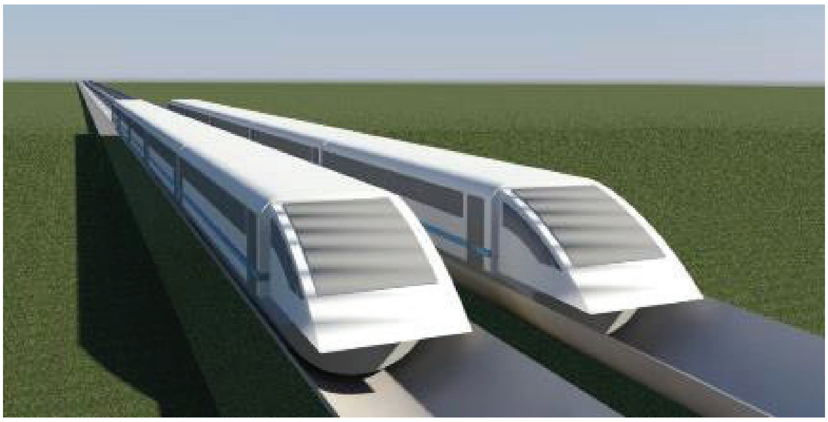


Fig. 38. System 2 – ProDynamic proposed

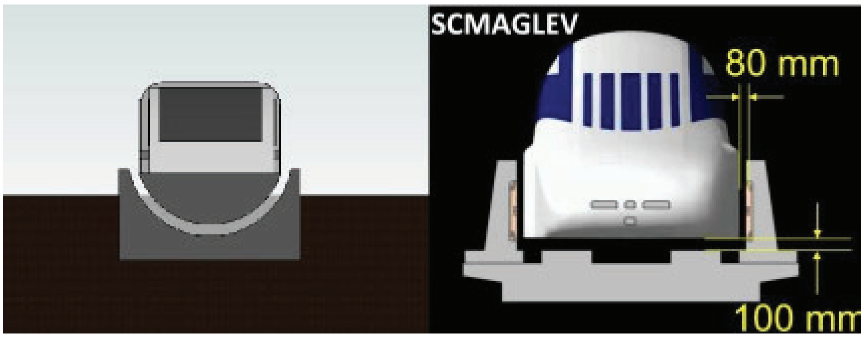


Fig. 39. System 2 – Comparison between the proposed system 2 and the SCMaglev system

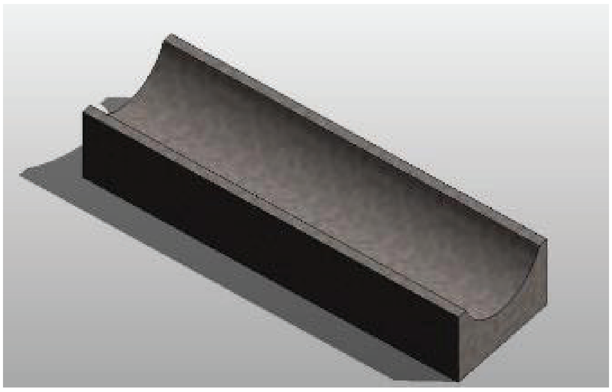


Fig. 40. Path to be used in system 2 proposed

The following image shows a cross section of the rail system proposed and its dimensions. As this track is continuous and always has the same geometric characteristics makes it very easy to build, and high-performance pre-fabrication can be used for a quick and economical solution.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

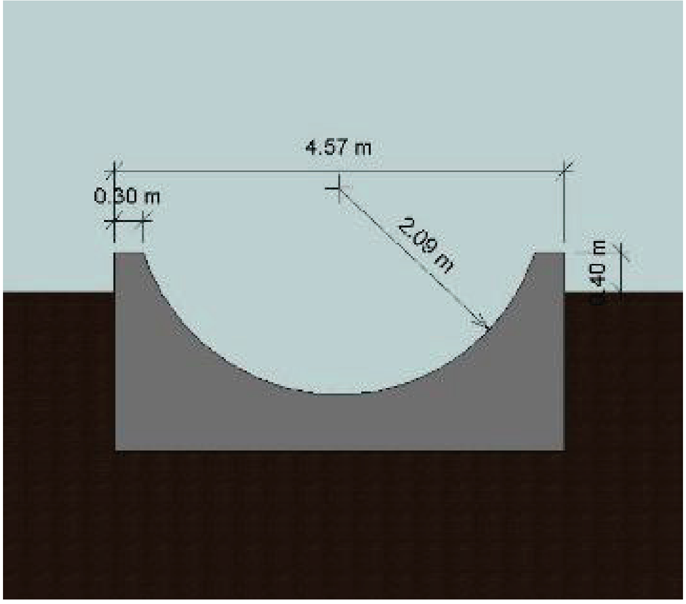


Fig. 41. Cross section of the proposed system 2 rail

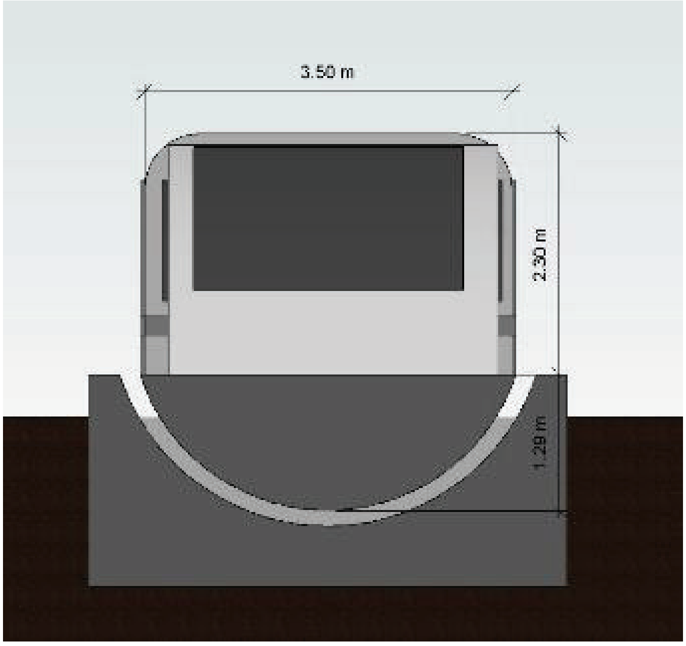


Fig. 42. Transverse perspective of system 2 vehicle

The following figure shows a cross-sectional view of the vehicle system 2 and its dimensions. As in system 1, system 2 is also like SCMaglev, differing only in the form of rail contact.

This system such as system 1 has a configuration that allows a maximum rotation of 12°. The system can guarantee an optimum relation between the speed at

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):77-111

doi: 10.17816/transsyst20184477-111

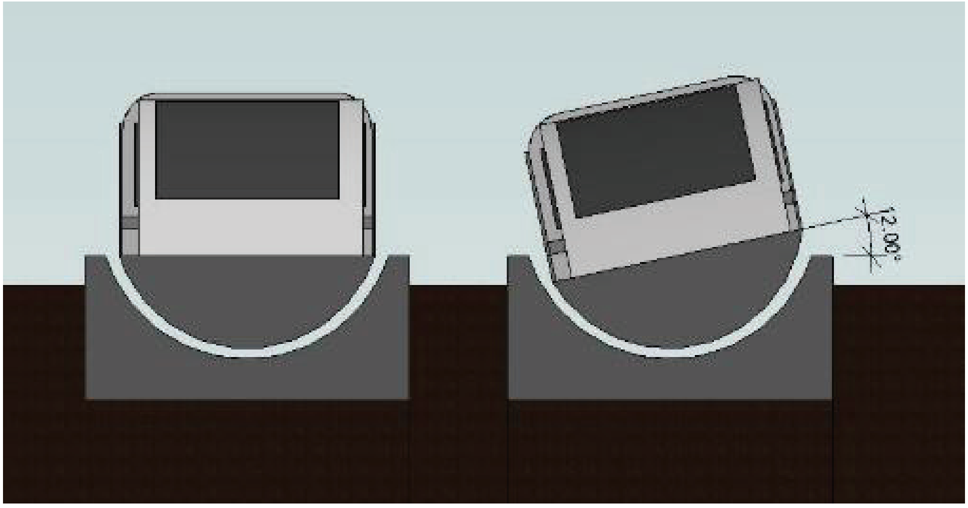


Fig. 43. Rotation of the vehicle in system 2 proposed

which the vehicle moves and the necessary speed for this speed, always maintaining the ideal comfort for the passengers.

The relationships between maximum operating speed, curved radius and slope of 12° are identical to the expressions in system 1. The minimum radius considered for this system was also 4400 m, so the results are the same.

This system, such as system 1, guarantees a good relationship between the degree of inclination of the operating speed and the comfort of the passengers, due to its simplicity in the construction, especially in a curve where this system does not require any type of superelevation.

CONCLUSION

After analysis it can be stated that high-speed railway lines are expanding all over the world, with several countries showing an interest in implementing the system or renewing their railway lines. However, based on the research developed in this work, high-speed systems probably reached the apogee of their development, at least for commercial speeds exceeding 350 km/h. The rail wheel contact system has physical limitations and problems such as lack of friction, which can compromise the security of the system or prevent the correct operation of the system.

Magnetic levitation systems represent the ideal alternative or complement to the current high-speed lines of the railways, since they are a system where there is no physical contact with the rail, eliminating any type of friction, being a system faster, quieter, with lower maintenance costs and more efficient energy consumption. They exhibit greater acceleration and greater braking capacity,

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):77-111
doi: 10.17816/transsyst20184477-111

managing to overcome superior longitudinal slopes and do not have problems of insufficiency or of excessive cant, like in railways.

In addition to these advantages, the systems presented in this work have evolutionary proposals that allow to reduce costs, especially in the construction phase, considering that the system does not require static superelevation in a curve. The cant is associated with the vehicle and not with the track, allowing continuous construction and the possibility of using prefabricated elements. As the vehicle is turning in a curve due to the existence of a magnetic field, there is no need superelevation of the track, reducing construction times, such as tight topography controls and proper adjustments to ensure the necessary inclination. The rail induces to the vehicle magnetic fields that serves, transverse guiding, sustentation along the rail, propulsion and braking, and the rotation that substitutes the cant, also defined by superelevation. Rotation of the vehicle is only performed in a curve, and this rotation has the advantage of adjusting the speed of the vehicle, ensuring the best comfort for passengers. The rotation being adjustable in a curve is more advantageous than an existing fixed cant for the entire life of the infrastructure. The vehicle may, for various reasons, can need travel at a lower design speed and if this happens and if the speed is lower than the design speed, passengers may feel the opposite effect of centrifugal force and pass to feel the centripetal force. This phenomenon is more evident if the vehicle stops in a curve, generating a lot of discomfort in the passengers, in the case of the static cant. So, when the rotation is performed in real time, for a certain speed, this system guarantees a better degree of comfort and if by chance the vehicle stops in a curve this adjusts automatically, as if it were a straight line. This control of the rotation, guiding, sustentation, propulsion and braking is realized by electronic control that adjust in real time all the parameters, guaranteeing the safety and the comfort of the passengers.

During this work it was found that levitation systems still present a higher implementation cost than existing high-speed railroad systems. However, given the lower energy consumption and the low costs of maintaining magnetic levitation systems, it can be said that the investment made will rapidly have a return expected in comparison to the railway systems.

The systems referred to in this work present a series of challenges and, to physically check their operational possibility, it will be necessary to carry out a scale model of the vehicles and the rails, so that the rotation of the curved systems can be checked. Prior to the execution of this model, several experiments should be carried out to verify how their various magnetic fields will behave when the vehicle turns in a curve through the introduction of a new magnetic force and how can these be calibrated and balanced forces. If it is possible to verify the operation of the system, there will be a need to check and size the rails for the two systems

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):77-111
doi: 10.17816/transsyst20184477-111

proposed here. In addition to the sizing of rails, construction methods can also be developed for each type of system in order to guarantee the highest productivity and the lowest possible cost.

Rotation of the vehicle and locomotion through magnetism may have applicability in other sectors of the industry, as has happened with the application of magnetic levitation in some elevators that are currently being developed.

Therefore, the systems presented here are an improvement to the proposed systems, however, it will be necessary to form a multidisciplinary research team in its various areas of science, to plan, experiment, adjust the systems from the project to its applicability and operation, thus guaranteed a significant improvement to a system that is already innovative.

The ProDynamic system is in this sense to give a new technological boost when the vehicle describes curves, thus avoiding any system of static infrastructure superelevation in the rail, or even complex mechanical hydraulic systems in vehicles that creates inclination of the vehicle. It is a theoretical system that lacks technical viability analysis in terms of electromechanical.

In conclusive terms, it can be said that if this system is technically feasible, the civil construction of the rail will be much more economical when compared to the current systems and in terms of comfort in circulation, the phenomena of insufficiency or excess of cant cease to exist.

References

1. Henry B, Comstock. *A Concise Illustrated History of the Development of Steam Traction*. Greenberg Pub; 1993. ISBN-10: 0897783573
2. Clifford F, Bonnett J. *Practical Railway Engineering*. 2nd ed. Imperial College Press; 2005. ISBN 10: 1860945155
3. Čermák JR, Bartoň L, Spal P, et al. Overview of Magnetic Levitation Principles and their Application in Maglev Trains. *Advanced Engineering*. 2008;2(1):19-28. ISSN 1846-5900. [cited 2018 June 9]. Available at: https://ru.scribd.com/document/55198430/magnetic-trolley-for-industrial-use
4. Zhou L, Shen Z. Progress in high-speed train technology around the world. *Journal of Modern Transportation.* 2011;19(1):1-6. doi: 10.1007/BF03325733
5. Sands BD. *The Transrapid Magnetic Levitation System: A Technical and Commercial Assessment*. The University of California Transportation Center CA 94720; no.183. [cited 2018 June 9]. Available at: http://www.maglev.ir/eng/documents/reports/IMT_R_16.pdf
6. Coelho A, Santos J, Soares A. A Via Ferroviária de Alta Versus Via de Levitação Magnética. Final dissertation, Project, ISEP, Porto, 2010
7. Siemens AG, Reserved AR. Shanghai Maglev Transrapid Technology. Propulsion Traveling Field, Trafikudvalget 2006.

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst20184477-111

8. Thome R, Radovinsky A, Montgomery B. EDS Levitation and Guidance Using Sheet Guideways 2 Magplane System Description 1 Introduction Design Issues for Sheet Guideways. 1992, no. 617. [cited 2018 June 9]. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.487.561&rep=rep1&type=pdf
9. Hoburg JF, Post RF. *A Laminated Track for the Inductrack System: Theory and Experiment* [cited 2018 June 9] Available at: http://www.askmar.com/Inductrack/2004-10%20Inductrack%20Laminated%20Track.pdf
10. The ROMAG Maglev GRT Technology. [Internet]. Washington University; c2015-03. Available at: http://faculty.washington.edu/jbs/itrans/romag.htm
11. Bachelet E. [Internet]. The International Maglev Board; c2015-03. Available at: https://www.maglevboard.net/en/facts/inventors/119-emile-bachelet
12. Transrapid Maglev in PR of China. [Internet]. The International Maglev Board; c2015-03. [cited 2018 June 9] Available at: https://www.maglevboard.net/en/pics/transrapid-maglev/35-maglev-board/pics/photos-images/116-transrapid-maglev-in-pr-of-china
13. Urban Magnetic Levitation (MAGLEV) Transit – Japanese HSST System. [Internet]. Washington University; c2015-03. [cited 2018 June 9]. Available at: https://faculty.washington.edu/jbs/itrans/hsstpage.htm
14. High Tech for "Flying on the Ground [Internet]. Transrapid International; c2015-06. [cited 2018 June 9]. Available at: https://www.ncl.ac.uk/media/wwwnclacuk/pressoffice/files/pressreleaseslegacy/TRI_Flug_Hoehe_e_5_021.pdf
15. Carvalho FO. *Elaboração de um Trilho MagLev Para Experimentos Didáticos*. [Internet]. Universidade Estadual de Campinas.; c2015-07. Available at: https://www.ifi.unicamp.br/~lunazzi/F530_F590_F690_F809_F895/F530_F590_F690_F895/F530_F590_F690_F895_sem2_2005/Fabricio_Dirceu_F895_RF2.pdf (In Portuguese).
16. Maglev: A New Approach [Internet]. Askmar; c2015-08. Available at: http://www.askmar.com/Inductrack/2000-1%20Inductrack%20Scientific%20American.pdf

Information about the authors:
Jacob Ângelo, Master degree Specialist, Adjunct Professor;
Dr. António Bernardino de Almeida str., 431, 4249-015 Porto, Portugal;
ORCID: 0000-0002-0998-4101;
E-mail: amj@isep.ipp.pt, angelo.jacob@civitrace.com

Monteiro Nuno, Master degree Civil Engineering, Infrastructures;
ORCID: 0000-0003-2150-1528;
E-mail: nunomanuelmonteiro@gmail.com

To cite this article:
Jacob AMG, Monteiro NMV. A New Concept of Superelevation in Magnetic Levitation – Prodynamic. *Transportation Systems and Technology.* 2018;4(4):77-111. doi: 10.17816/transsyst20184477-111

Received: 15.09.2018. Revised: 12.10.2018. Accepted: 17.12.2018.

DOI 10.17816/transsyst201844112-128

© E. Chao[1], **J. Venturi**[2.]
[1]University of Pennsylvania, Department of Electrical and Systems Engineering
(Philadelphia, USA).
[2]Rethink Studio
(New York, USA)

OPERATIONAL BREAKDOWN AND PERFORMANCE MEASURE OF THE TRANSCONTINENTAL HIGH-SPEED MAGLEV

Background: Magnetic Levitation (Maglev) systems have a noticeable operating track record in about a dozen countries. Higher speed maglev technology has been built for many intercity and regional lines in China, Germany, Japan, South Korea, United States, Brazil, and other countries. Maglev developers claim that the transcontinental high speed system can outperform the existing HSR and air transport and can achieve higher speed, have lower energy consumption and life cycle costs, attract more passengers, and boost regional economy. The article presents a systematic breakdown of the proposed transcontinental high speed Maglev system and pinpoints critical operational components and implementation measures. The analyses reach the following discussions on the three most important system characteristics.

Firstly, the transcontinental high speed Maglev had to make trade-offs among passenger access time to total travel time, station density to daily maximum operating speed, and operating strategy to daily skip-stop, express, as well as other accelerated services.

Secondly, the correlation between systems capacity management and vehicle interior space design (e.g. seats) has a serious impact on operators' long-term financial condition. The involvement of identifying the equilibrium between these two factors in a linear algebra method is substantial.

Thirdly, the transcontinental high speed Maglev station must serve as the multimodal transportation hub. To attract passengers; accordingly, increase the ridership and farebox recovery, an unified transfer service on schedule coordination has to be incorporated into the system. Timed Transfer Systems (TTS) had the proven capability of increasing service reliability across different modes. Based on these discussions, the framework and direction of transcontinental high speed Maglev strategic planning is becoming sensible.

Aim: The article addresses the major system design elements of transportation planning and pinpoints corresponding operational strategies, which are useful for the planning and design of maglev. The study will assist system designers, network planners, and operators to understand where the technical and operational boundaries are for this particular mode. Knowing the boundary is useful for the design, planning, and operations of the system.

Methods: The efforts of literature reviews focus on two fields: composition of major system design elements and interrelation with other modes of transportation. The method examines the foundation of maglev planning.

Results: First, the benefit of speed increase cannot be hasty generalized. The assessment of speed increase needs to break down to different beneficiaries (e.g. operator, passenger, and the community). Second, system capacity depends on its operating speed, service frequency, load factor, and vehicle size. These four factors further determine the operational feasibility of

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

the maglev. Finally, in a dispersed travel pattern, TTS increases transfer reliability and unifies different lines of headway to improve service reliability.

Conclusion: Certain cities and countries are facing similar transportation issues. They are trying to learn from each other. The efforts focus on the establishment of efficient transit systems and the dedicated action to adopt a new mode of transportation (e.g. maglev) for intracity, intercity, transcontinental commutes. The article offers tangible values on transportation planning, systems design, and operation performance, which are critical for the development of the maglev system.

Keywords: Transcontinental Maglev, Strategic Planning and Implementation Measures, Systems Design, Operation Performance

INTRODUCTION

The feasibility and application of low, medium, and high-speed maglev to intracity, intercity, transcontinental commute are receiving more and more attention. For example, Changsha Maglev Express is the first low-medium maglev line in China with an average speed of 65 km/hr [1]. Virgin Hyperloop One, Hyperloop Transportation Technology, and Hardt Hyperloop are dedicated to developing transcontinental high-speed operational prototypes for both passenger and freight [2–4]. While these firms are trying to commercialize the high-speed maglev system, many interesting challenges lie in front of it. Invalid transportation planning concepts spread out on the internet by claiming that the system will be an on-demand service without a fixed schedule [5], which failed to consider the interrelations between station density, area coverage, and passenger access time as well as total travel time. At a technical level, the new system is particularly sensitive to station density, area coverage, vehicle size, vehicle capacity, throughputs, and many other operational elements while pursuing the maximum speed.

AIM

The article addresses the common system design elements of transportation planning and pinpoints corresponding operational strategies. The study will assist system designers, network planning, and operators to understand where the technical and operational boundaries are for this particular mode. Knowing the boundary is useful for the design, planning, and operations of the system.

ANALYSES

No matter for the intracity (low and medium speed) or intercity or transcontinental (high speed) maglev system, many transportation planning trade-

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844112-128

offs have to be considered. The first trade-off refers to passenger access time and travel time. The purpose of establishing a station is to provide a convenient access to the passenger, but too many stations would increase travel time due to the corresponding halts. Thus, evaluating the conflict of station density and speed could assess whether the advantages of speed increase outweigh the disadvantages. Second, system capacity depends on its operating speed, service frequency, load factor, and vehicle size. Examining these four factors would clarify its operational feasibility. Finally, the computation of TTS schedule and its pros and cons are given.

1.1. System design

Passenger Access and Travel Time. The travel time of passengers on transit line passenger time (PT) consists of two main concepts: access to/from the stations, including waiting for a train PT_a and travel time on the line PT_t as shown in Fig. 1 [6].

$$PT = PT_a + PT_t \quad (1)$$

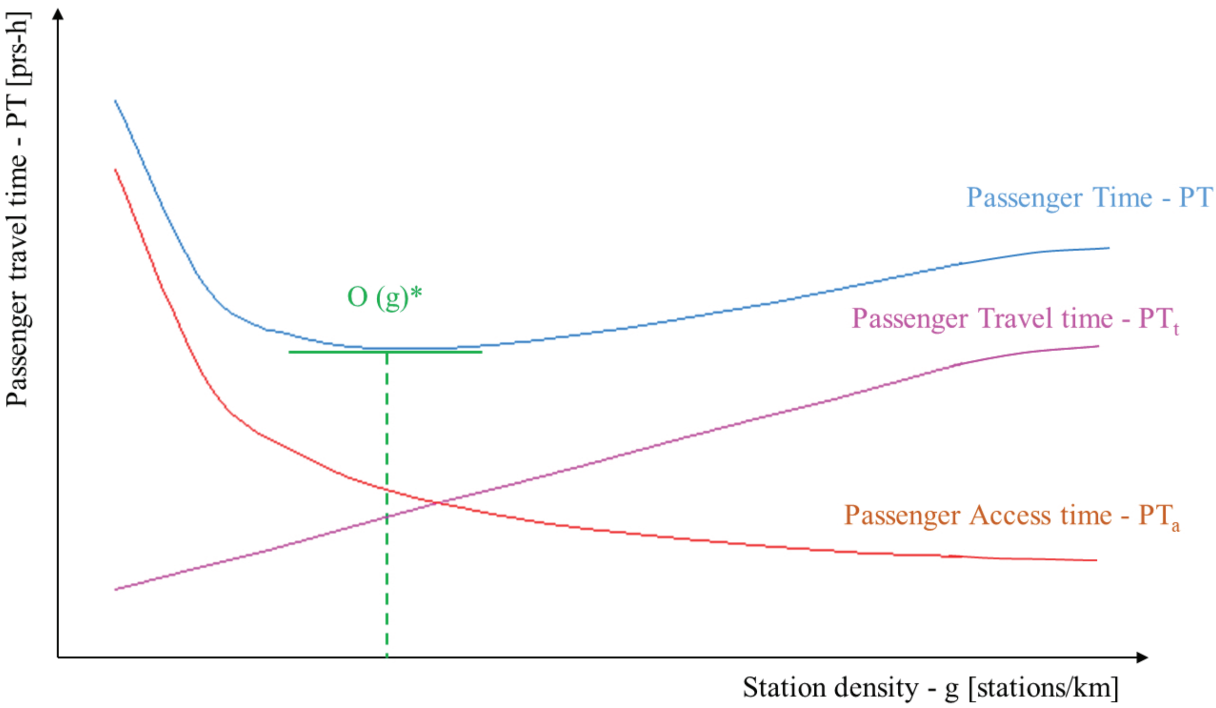


Fig. 1. Passenger travel time as a function of station density [6]

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

The number and locations of stations along a line influence both access and travel time. The number of stations on a line with a given distance is often analyzed through the station density – g, defined as station per km, or the inverse of the average station spacing. For example, if the average spacing is 0.8 km, station density is g = 1/0.8 = 1.25 station/km.

Considering passenger travel times, station density must be based on the optimum value trade-off between access (PT_a) and travel times (PT_t).

1. The increase of station density – g results in a decrease of average distance and access time to station PT_a

2. The growing of station density – g on the line results in the increase of passenger travel time – PT_t

When station spacing becomes too short that trains cannot reach their maximum speed, the additional delay happens so that the marginal increase in travel time begins to decline. The total passenger travel time curve PT shows an optimal station density – O(*g*)*. If passenger distribution along a line is uniform, the optimal station density is determined by the trade-off. If passenger distribution is non-uniform, such distribution influences the optimal station locations and results in variable spacing [6–7].

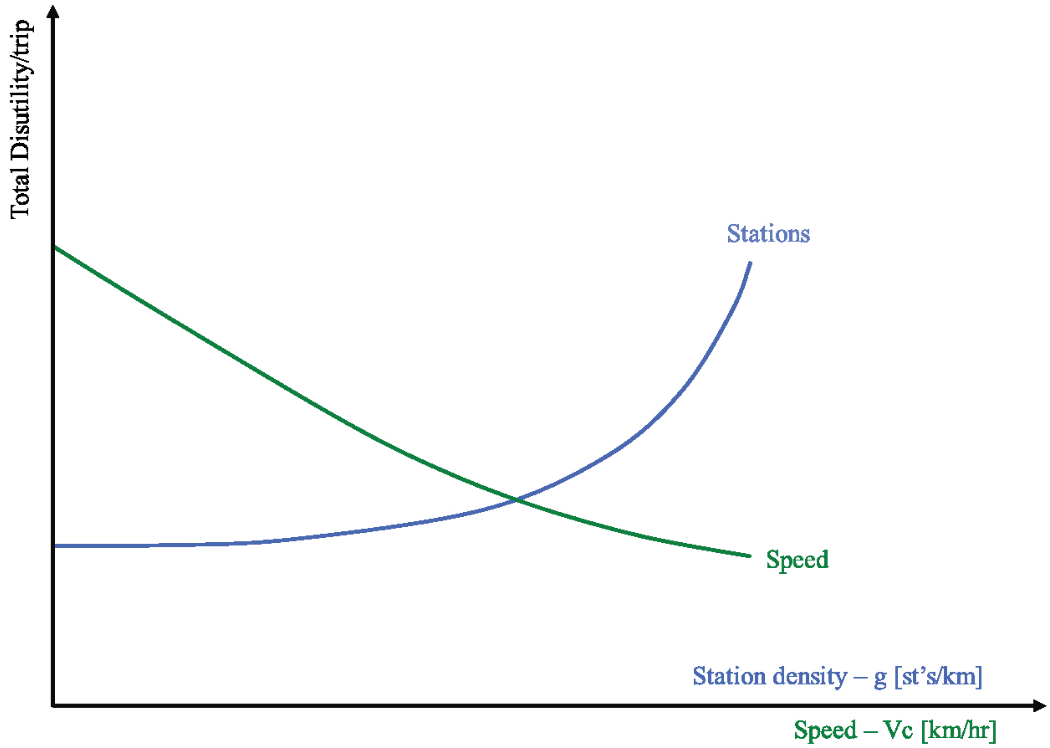
Planning of stations faces a basic dilemma: closer stations (short spacing in between) result in better area coverage and easier access for a larger number of potential passengers. However, short station spacings cause lower operating speed and possibly larger vehicle size, as well as higher construction and station maintenance costs. Longer station spacings result in the opposite situation: high speed and better operation, but with a line passing through areas without serving them, since there are no stations. A portion of potential passengers is then lost [8].

Station Density vs. Speed. Transit operation has a sensitive relationship between the number of stations and speed or disutility. As shown in Fig. 2, when station density g [st's/km] is low (say, only two terminal stations for a single line), travel speed can go very fast, but the total disutility is also very high, mainly due to lots of unserved areas (resulting in low ridership). As the station density increases, speed will become lower, then more passenger will be served although the overall travel time increases. This also results in a lower cost per passenger.

Fig. 3 shows distribution of Q stations in a single line (from the left) and speed (from the right). Transit operators mostly operate trains under the lower disutility scenario, the distribution between stations and speed will be at the equilibrium point E: q_g, the number of station, and q_{vc}, the operating speed. This situation can be seen in the real world where there is a high-speed maglev with an average speed of 350 km/hr and a high-speed rail (HSR) line with an average speed of 250 km/hr. If one could make an impact on the other, for example, Δq

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128



Disutility: user cost, travel time, unserved areas, system externalities

Fig. 2. Travel disutility by station density and speed

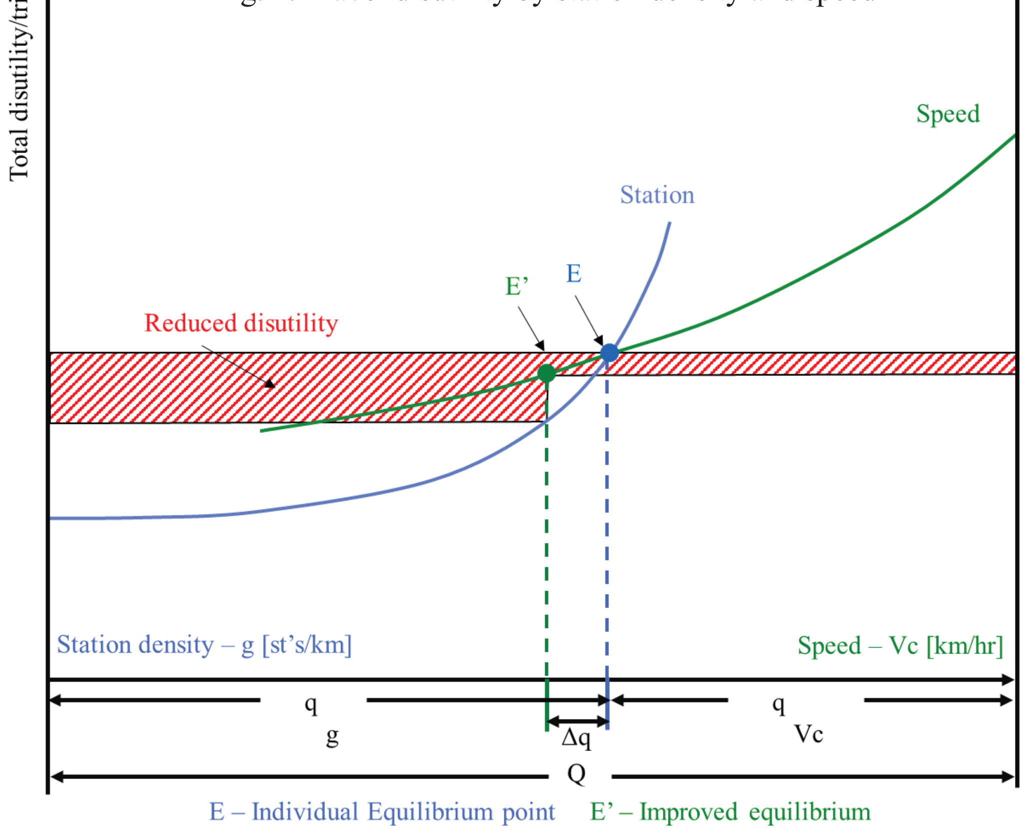


Fig. 3. Travel distribution between station density and speed

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

shows the number of travelers deciding to travel on a single line when the number of stations decreases, its operating speed can be increased. Therefore, the travelers on the line would benefit, so identifying station density and speed leads a system optimum – minimum total disutility.

Maglev system plans to challenge the existing modes of transportation or create a new mode to massively shorten the citywide commuting time. One must understand this relationship between station density and speed, and they apply two sets of design principle or operating strategy to plan for a "***flexible***" maglev. The term "flexible" in transportation systems planning always comes with trade-offs [9]. As abovementioned, the trade-offs are between passenger access time and passenger travel time as well as station density and speed. Thus, if pursuing the maximum speed of this new mode of transportation, one should understand the importance of the two sets of interchangeable design principles:

• Method I: Increase speed;

• Method II: Decrease station density.

Fig. 4 shows how these two sets of measures result in a shift of the equilibrium point from the individual equilibrium point (IE) toward the system

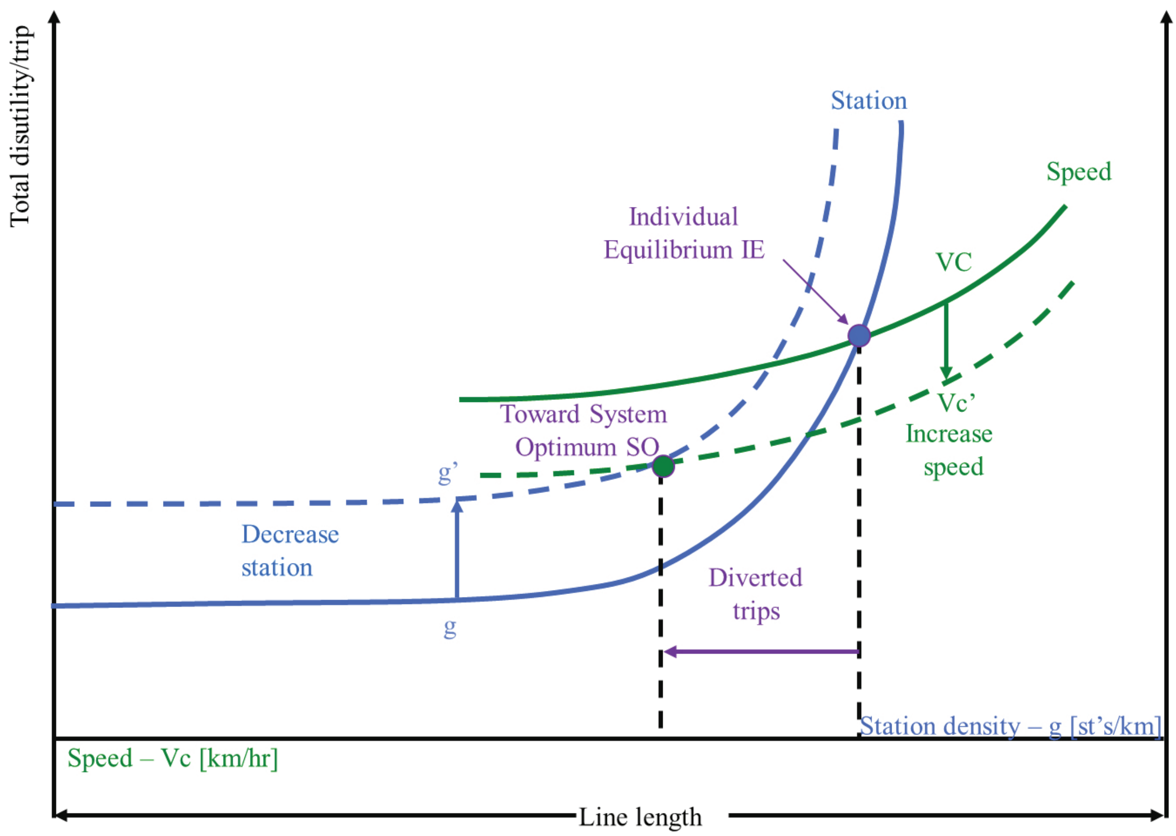


Fig. 4. Operation strategy for shifting individual equilibrium to system optimum

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

optimum (SO): to increase speed move the V_C curve down to V_C', whereas station density moves the g curve up to g'. The result is a shift of operating more stations to fewer stations so that trains can travel at a higher speed, known as skip-stop and express services, this goes from the initial IE toward the SO by the individual decisions of travelers and operator, and it remains stable there. The diagram shows that the total disutility of travel in both modes, which was initially at the IE level, and has been reduced to SO.

The corresponding operation measure of station spacing on any section along a line should be a function of the ratio of the number of passengers with origins and destinations along the ridership distribution vs. the number passengers on the trains passing though the same section preferring to skip the stop due to time loss. The greater of this ratio, the more the station be established. On the other hand, where the volume of through passengers dominates the volume of local passengers, station spacing should be long. In the extreme case, if there is a section without any passengers waiting to board and alight, there should be no stations. An important consequence of this relations is that, with respect to passenger time (PT), uniform/fixed station spacing is seldom optimal. Overall, station density – g varies with the distribution of passenger demand along the line [6–8].

After addressing the interrelation and trade-off of passenger time, station density, and speed, cost of stations is worth to be discussed.

Cost of stations. Each station involves certain investment cost and operating cost for station operation and maintenance, stopping trains, and for larger transit unit due to longer cycle time. For equal local conditions, the incremental cost per station is constant when station are far apart, but it decreases slightly when spacings become so short that trains cannot reach maximum speed because the incremental time and energy consumption per stopping are then slightly reduced. Thus, the total cost of stations increases with their density, but at a decreasing rate, as plotted in Fig. 5 [6].

In a nutshell, identifying the optimal station density by overlapped multiple operating factors is able to find the optimal value for station density as Fig. 6. shown. Among all these factors, passenger time is the most decisive factor and has a strong correlation with station density.

1.2. System capacity

Optimal Vehicle Size & Capacity. To analyze how maglev system could outperform other transit modes under which conditions, it is critical to understand

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):112-128
doi: 10.17816/transsyst201844112-128

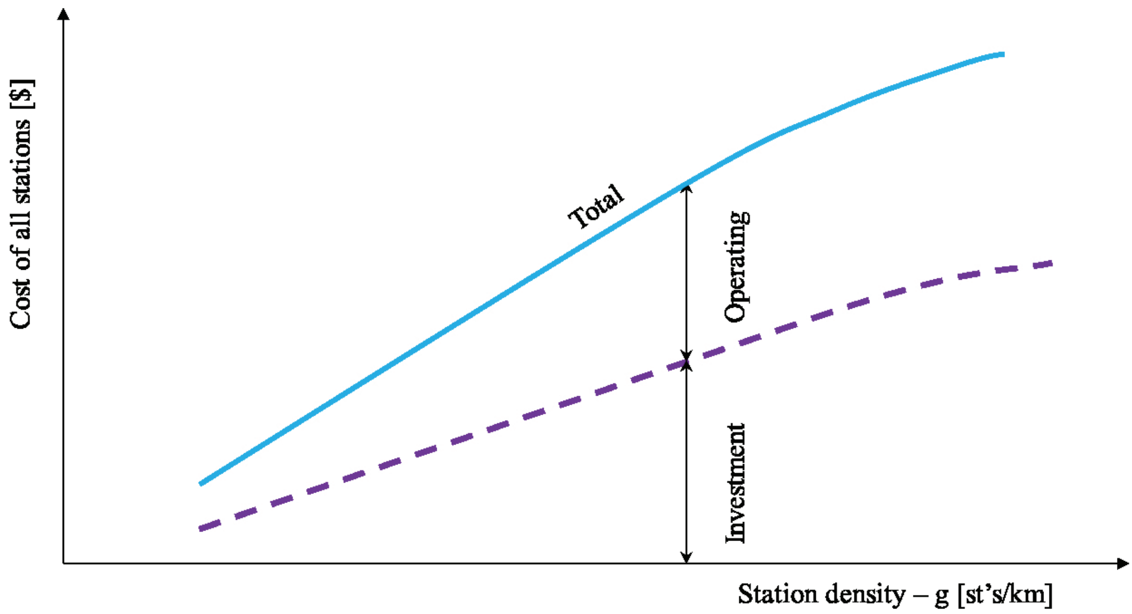


Fig. 5. Total cost (investment and operating) of stations by density on a fixed line [6]

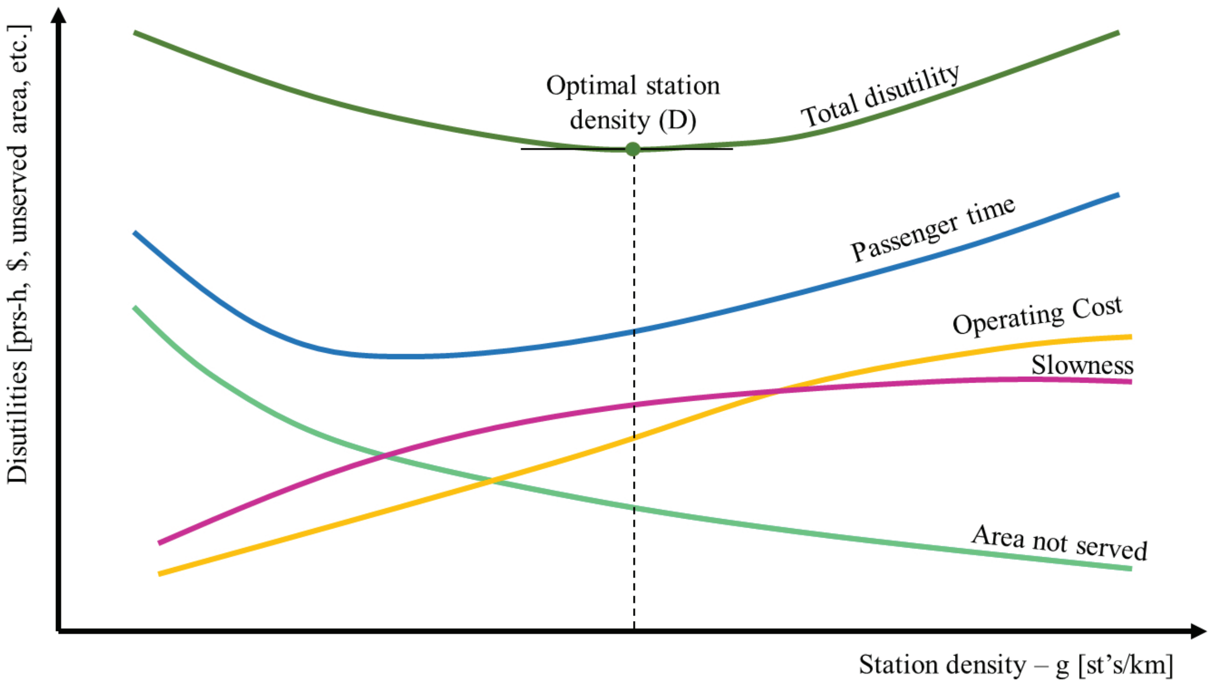


Fig. 6. Optimal station density on network planning [6]

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

the system capacity and operation boundaries. One of the common methods to distinguish modes is the vehicle size associated with system capacity.

Fig. 7 shows the relations among service headway, transit unit (TU) capacity, and the line capacity. To challenge the existing modes of transportation, one must firstly define the operating boundaries with a holistic consideration of vehicle capacity and size of transport units. The critical condition for which every system must be designed is the peak hour, precisely, the maximum passenger volume expanded to hourly volume. From an operation perspective, it would be financially difficult to justify the exclusive right-of-way (ROW) and the investment of a fully automated system if its design capacity were less than 2000 sps/hr or actual passenger volume between 1500 to 1800 prs/hr. For example, at Point A1 and A2, the system is able to ship 25×50 and 10×100 [frequency × space] units respectively per hour. However, the operating cost and passenger/cargo per unit cost is high compared to Point B (3000 psr/hr) and Point C (7200 prs/hr). Therefore, the maglev system capacity is very volatile to TU capacity, ideally greater than 50 spaces for passengers TUs [10].

The operation domain is the limit of the purple-dashed box. The left boundary is limited due to TU capacity, that is, the offered spaces. The right

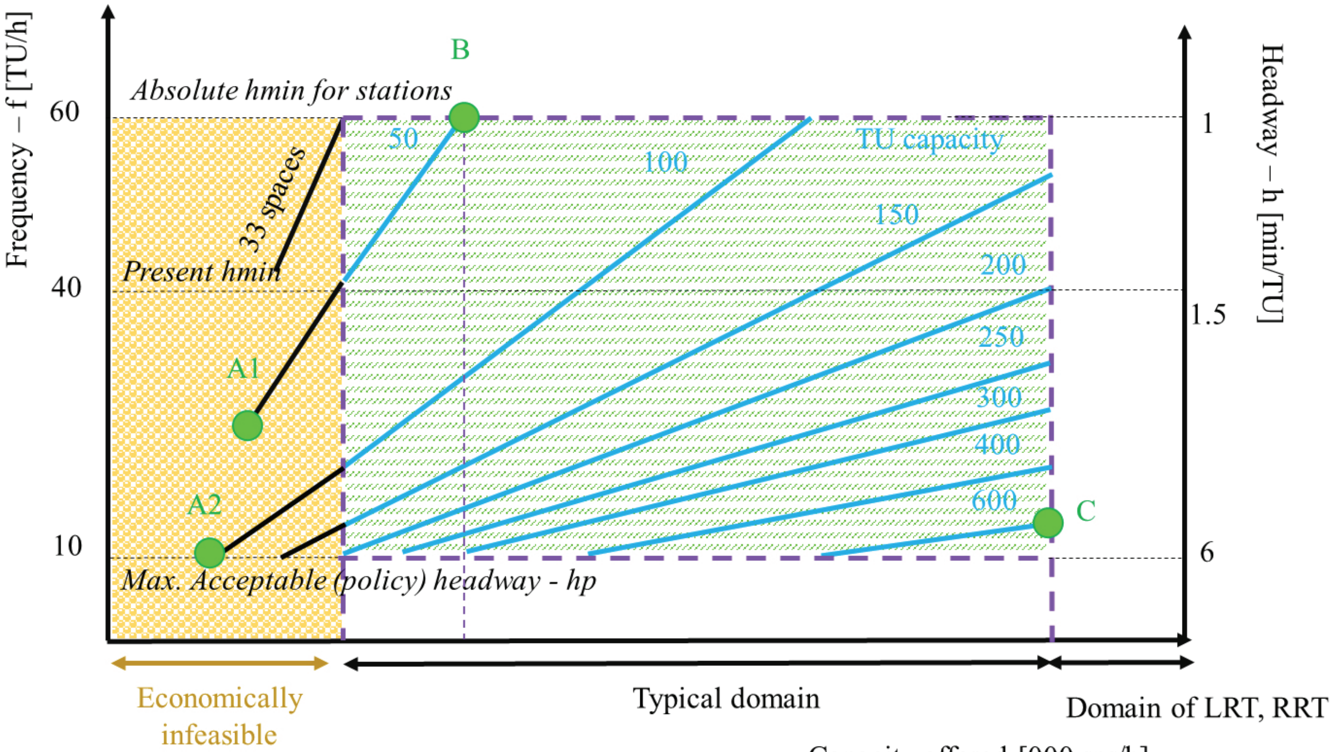


Fig. 7. Transit unit capacity by frequency and line capacity [10]

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

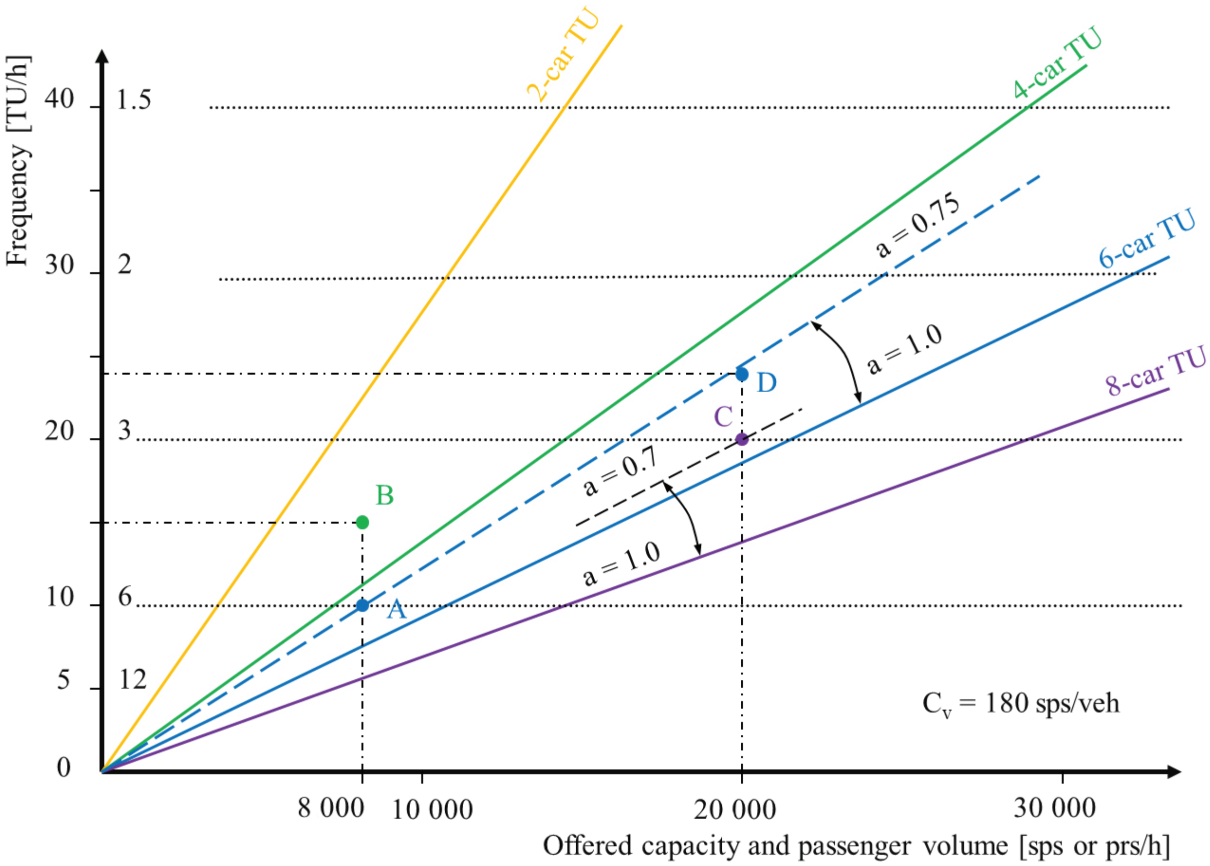


Fig. 8. Operation strategy: transit unit capacity and headway on schedule design [6]

and bottom boundaries are limited due to its maximum TU capacity with the consideration of headway simultaneously. The fact is that large vehicles cannot run short headway considering the length of the vehicle and safety distance. Around the globe, Moscow and Barcelona metros have had experience with operating vehicles within 75 sec (48 TU/hr) of headway with a 6-car train and 90 sec (40 TU/hr) headway with a 5-car train respectively under Automated Train Control (ATC) [11–12].

Assuming the maglev TU capacity were smaller than these two metros' both TU length and capacity will able to operate its fleets with 60 sec headway (60 TU/hr), then the upper boundary were to be established. Such an approach has been commonly used in linear algebra. Considering all the above, a typical operating domain falls into the green area.

Guidance of TU Size, Frequency & Load

Fig. 8. can be used to select the optimal combination of transit unit (TU) size – n, operating speed – C_v, service frequency – *f*, headway – h, and load factor – α for any scheduling period of the day.

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

The diagram is based on the equation:

$$C = n\ x\ C_v\ x\ \alpha\ x\ f \qquad (2)$$

The equation shows four different trains consisting of: TU sizes of 2, 4, 6, 8-cars, and the line capacity with operations at different frequency/headway and load factor α. Each slope line shows the values for a given TU size at full occupancy, α = 1. A blue-dashed line shows the capacities offered by six-car TUs with α = 0.75.

Assumed offered capacity is 180 seats per vehicle. During mid-day period P_{max} – 8,000 prs/hr, reasonable choices would be to operate 6-car TUs at h = 6 min with α = 0.75 – point A on the diagram; or 4-car TUs at h = 4 min with α = 0.75 – point B. Suppose that the peak period has P_{max} = 22000 prs/hr; then the choices may be to operate 8-car TUs at h = 3 min and α = 0.70 – point C, or 6-car TUs at 2.5 min and α = 0.77 – point D [6].

After examined the major system design elements of transportation planning, it is time to analyze the interdependent operation strategies across different modes. That is, how could one system work cooperatively with another to create a cohesive schedule to increase overall passenger gain and system ridership.

1.3. System unification

Timed Transfer System (TTS) is a network consisting of several transit lines and one or more transit centers at which transit units from all intersecting lines arrive simultaneously, allowing passenger transfers in all directions. TTS coordinates different lines’ schedule and commonly used in medium-sized cities and suburban areas to fulfill the seamless integration and connectivity. Without the application of TTS, passenger transfers among lines involve a higher «resistance», because a transfer may cause delay and require passenger re-orientation and extra walking between mezzanines and platforms on different lines [6, 13–14].

TTS SCHEDULING

• In an uncoordinated scheduling system (Fig. 9a.), the basic operating elements (length, cycle time, fleet size, operating speed, and number of vehicles or transport unit on a route) for each route are independent in the network.

• In TTS network the headway (and therefore frequency) must be the same on all routes (Fig. 9b.), or an exact multiple of headways on other route, only with

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844112-128

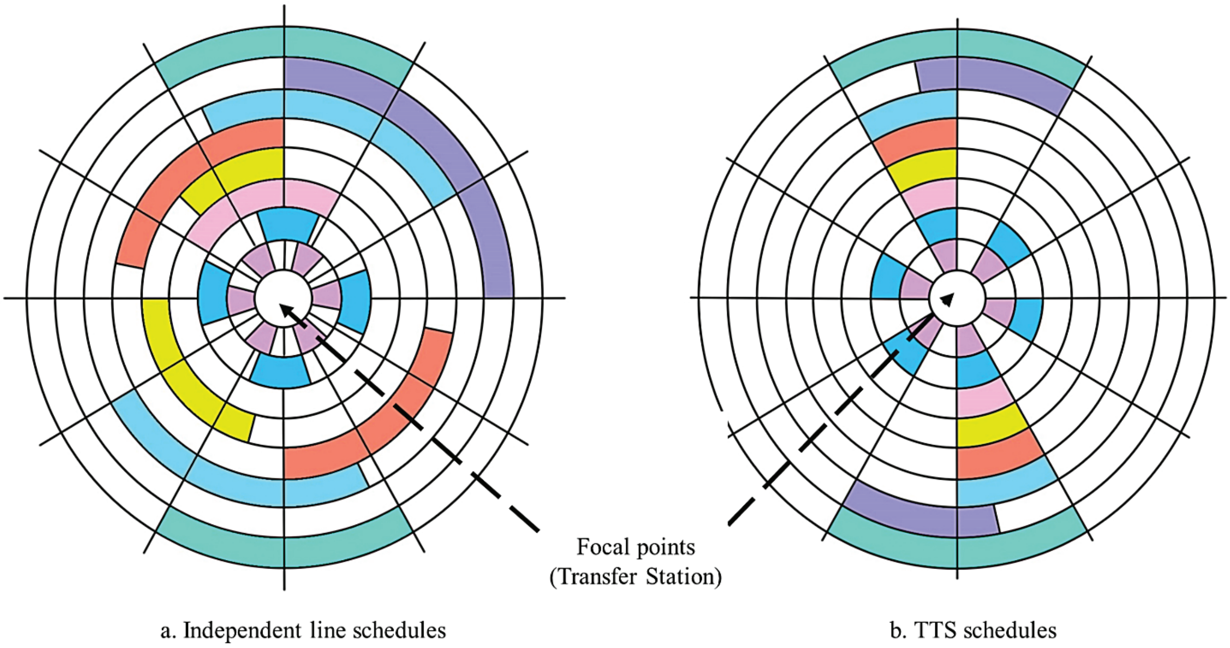


Fig. 9. Clock-type diagram showing two types of line schedules at a transit center [13]

few exceptions for special purpose. For example, all routes coming to a focal point or transfer station must have headways of 5, 10, 15 min, or exceptionally, 30 or 60 min. Headways are required to be divisible into one to enable easy memorization of schedules by passengers.

• The value of very short pulse headway (*h*) can be used only on high reliable systems with a fully controlled Right-of-Way A. As a Virgin Hyperloop One video shown, the systems have simultaneous arrivals of vehicle or transport unit from different lines and exchange of passenger (every 5, or even every 2.5 mins) [14]. However, such short headways could increase operation and maintenance cost. Another aspect should be considered while planning the headway is the demand, level of services, and expected reliability of service on each route.

• For every case, each line must have the same headway. That is, the same ratio of cycle time and number of transport units on the line [6, 13]:

$$h = \frac{T1}{N1} = \frac{T2}{N2} = \ldots\ldots \tag{3}$$

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

TTS PROS AND CONS

TTS execution relies on the same ratio of cycle time and number of TUs on the line. Compared with conventional operation, TTS has the following advantages (+) and disadvantages (–):

+ Transfers among all routes meeting at each transit center are much faster and more convenient;

+ Transit service represents a multidirectional, unified network serving a variety of trips, as opposed to services restricted to individual routes in networks without convenient transfers;

+ Large, distinct terminals provide a much greater number of services than smaller ones for individual routes;

+ Due to the better services (network, schedules, public image, terminals), TTS attracts a substantially larger patronage and plays a more important role than conventional networks;

− TTS generally requires a higher investment (terminals, information) and operating costs (more vehicles on routes), which may or may not be offset by higher revenues;

− Some passengers may have less direct routing and additional delays during layovers of through routes at transit centers;

− TTS is more vulnerable to delays: missed expected connections cause considerable aggravation of passengers;

− "Pulsing" at terminals may cause congestion on access routes and it requires large terminal capacities [13].

CONCLUSION

The diversity among cities and countries in terms of their historic, geographic, social, and strategic positions dictate to the requirements for a variety of approaches and solutions to urban transportation problems. Policies and solutions cannot be directly transferred from one to another; however, many fundamental problems are similar, and the exchange of experience can be useful in resolving the sophisticated problems faced by cities.

Many global cities are either in the transition stage of rethinking cities' long-term competitiveness or in the development stage of large-scale city and regional planning. Common facts have been found in these two settings: the outstanding commitments on the selection and establishment of efficient transit systems and the

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844112-128

dedicated action to adopt a new mode of transportation (e.g. maglev) for intracity, intercity, transcontinental commutes.

While cities are trying to learn from each other, a dedicated effort to understand systems design and operational measurement is indispensable. Transit system, by nature, has its own boundary. The boundary needs to be meticulously studied. Fig. 10 shows an evaluation of speed increase to different beneficiaries. In addition, vehicle size has a strong correlation with system capacity and maximum load. Knowing system's capacity and operation limitations are useful to examine whether one system could outperform another under which condition. Fig. 11 shows whether the maglev system could outperform the existing modes depend on speed, cost, and ridership. The condition is given under the same line capacity so that the operating speed of medium-speed maglev is higher than light rail in a right-of-way B environment and high-speed maglev is operating faster than HSR in a right-of-way A environment.

The emerging of a new mode is to complement the existing one, rather than compete with. After all, different modes have different functions. Therefore, TTS is an implementation tool to coordinate different lines of headway to increase system reliability and seamless transfers. TTS improves service cohesiveness where travel

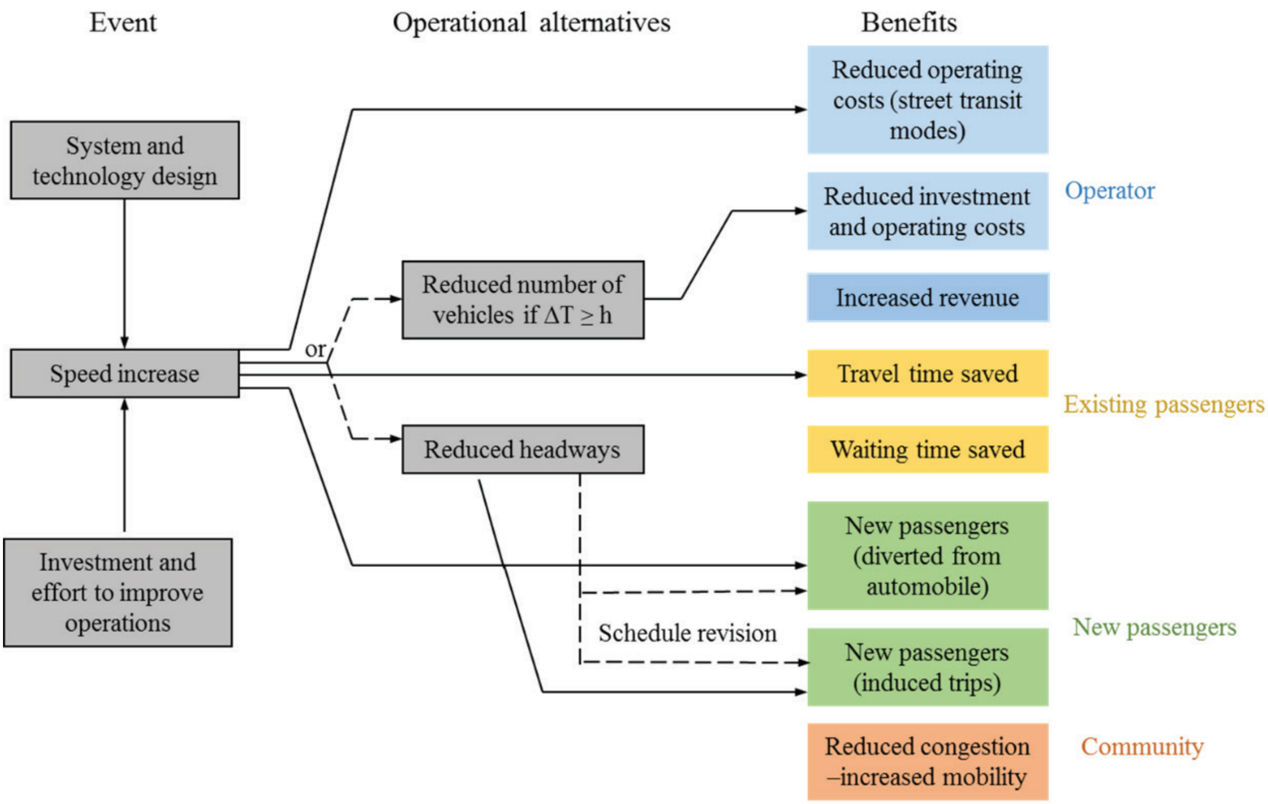


Fig. 10. Evaluation of speed increase [10]

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

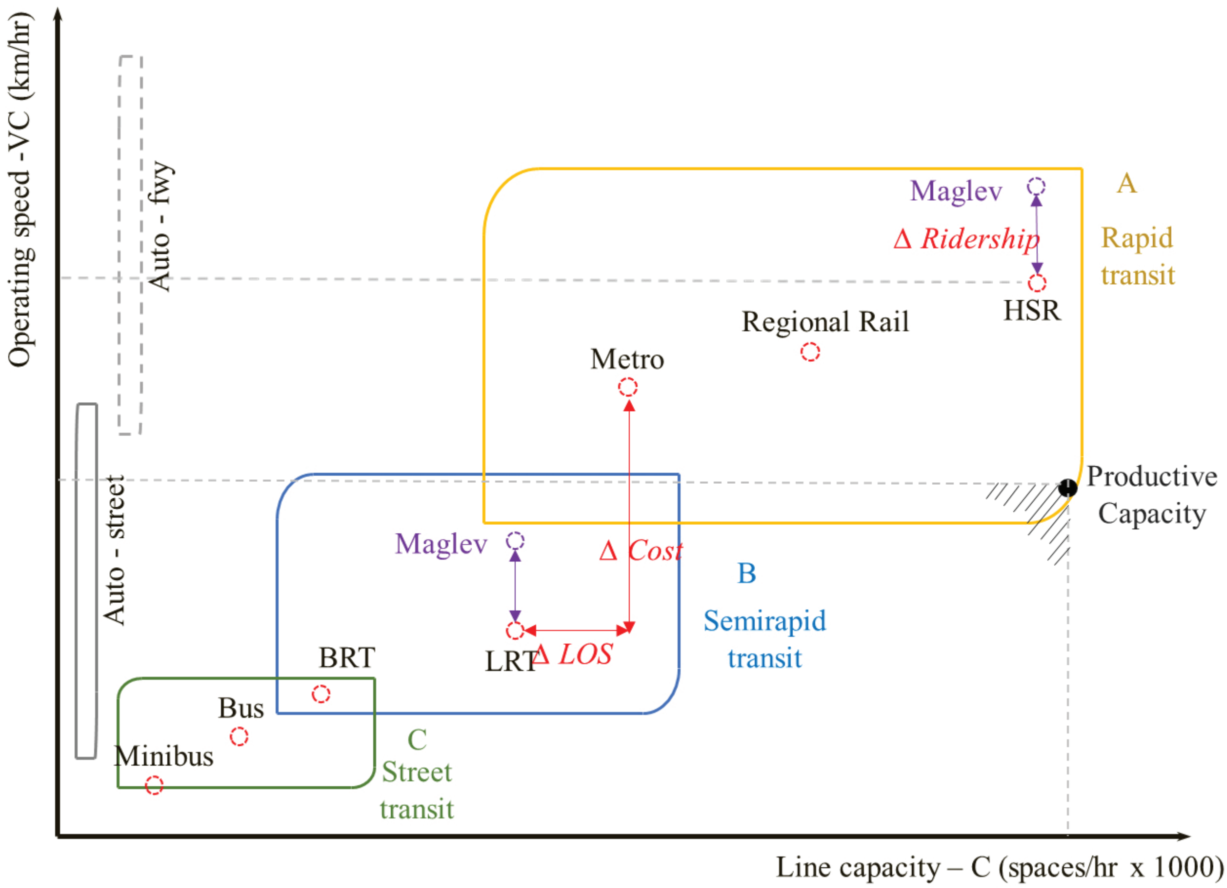


Fig. 11. Line capacity, operating speed, and productivity capacity by modes [6]

demand is characterized by dispersed O-D patterns (many-to-many) and demand density is rather uniform and major trip generators are located at several locations dispersed throughout the areas, with moderate concentrations at each one. This results in the demand for transit routes with rather similar headways converging on several different nodes.

While developing a new mode of transportation no matter for intracity, intercity, or transcontinental, certain efforts need to be carried: reducing the total disutility and avoiding mutually conflicting policies to achieve an intermodal balanced transportation system. A plan always comes with a purpose. A broad vision of the city-transportation relationships and the creation of unified services are interdependent with counties' long-term economic outlook [15–17].

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):112-128

doi: 10.17816/transsyst201844112-128

References

1. Changsha Maglev Express [Internet]; 2017 [cited 2018 May 12] Available from: http://enghunan.gov.cn/SP/ChangshaMaglevTrain/.
2. Virgin Hyperloop One [Internet]; c2017-2018 [updated 2018]. Available at: https://hyperloop-one.com/.
3. Hyperloop Transportation Technology [Internet]; c2017-2018 [updated 2018]. Available at: http://www.hyperloop.global/.
4. Hardt Hyperloop [Internet]; c2017-2018 [updated 2018]. Available at: https://hardt.global/research.
5. Lloyd R. A New Cargo Brand Built For An On-Demand World [Internet]. Los Angeles: Rob Lloyd. 2018 Apr [cited 2018 May 12]. Available at: https://hyperloop-one.com/blog/new-cargo-brand-built-demand-world.
6. Vuchic VR. Urban Transit: Operations, Planning, and Economics. Hoboken, NJ: Wiley & Sons. 2005.
7. Vuchic VR. Rapid Transit Interstation Spacings for Maximum Number of Passengers. Transportation Science. 1969;3(3):214-232. doi: 10.1287/trsc.3.3.214
8. Vuchic VR, Newell GF. Rapid Transit Interstation Spacings for Minimum Travel Time. Transportation Science. 1968;2(4):303-339. doi: 10.1287/trsc.2.4.303
9. Vuchic VR. Concept of Flexibility in Transportation System Analysis. High Speed Ground Transportation Journal. 1971;5(1):53-61.
10. Vuchic VR. Urban Public Transportation Systems and Technology. Englewood Cliffs, NJ: Prentice-Hall; 1981.
11. Moscow Mayor Official Website. Moscow Metro to launch fourth automated train [Internet]. Moscow; 2017 [cited 2018 May 12]. Available from: https://www.mos.ru/en/news/item/20965073/.
12. TMB. Barcelona's driverless line 9/10 automated metro project [Internet]. Spain; 2018 [citied 2018 May 12]. Available from: https://www.tmb.cat/en/about-tmb/transport-network-improvements/automated-metro/which-lines.
13. Vuchic VR, et al. Timed Transfer System Planning, Design and Operation. Report DOT-I-83-28 to UMTA, DOT. Washington; 1983 Oct.
14. The Hyperloop One System – UAE [video]; Virgin Hyperloop One Nov 8, 2016 Available at: https://www.youtube.com/watch?v=fze5spdN3nU. Accessed: November 8, 2016.
15. Vuchic VR. Livable Cities - Will Transportation Professionals Answer the Challenge. Transportation Research News. 2003:22-26.
16. Vuchic VR. Transportation for Livable Cities. New Brunswick, NJ: CUPR, Rutgers University. 2010.
17. Gehl J. Cities for People. Washington, D.C.: Island Press; 2010.

Received: 17.10.2018. Revised: 17.10.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844112-128

Information about the authors:

Eugene (Wubin) Chao, Technical Assistant for Dr. Vukan R, Vuchic, University of Pennsylvania, Department of Electrical and Systems Engineering, Towne Building 220 South 33rd Street, Philadelphia PA 19104-6315, U.S.A

E-mail: chawu@alumni.upenn.edu

Jim Venturi;

E-mail: jim.venturi@rethinkstudio.org

To cite this article:

Chao E, Venturi J. Operational Breakdown and Performance Measure of the Transcontinental High-Speed Maglev. *Transportation Systems and Technology.* 2018;4(4):112-128. doi: 10.17816/transsyst201844112-128

DOI 10.17816/transsyst201844129-137

© Y. Yang, W. Zhang, L. Tong, Q. Peng, H. Luo, J. Suo
CRRC Zhuzhou Locomotive CO., LTD
(Zhuzhou, China)

ANALYSIS AND SOLUTION OF EDDY CURRENT INDUCED IN RAIL FOR MEDIUM AND LOW SPEED MAGLEV TRANSPORTATION SYSTEM

Background: For medium and low speed maglev transportation system, the eddy current will be induced in rail, which is made of solid steel, while the train is running. The levitation force of electromagnets will be weakened by the magnetic field generated by eddy current in the rail, especially at the position of the forefront electromagnets. With the increase of train running speed, the eddy current effect will also increase, which will reach 30 % at 100 km/h, and which will directly affect the levitation stability of the train during high-speed running. Put it another way, it will limit the further improvement of the running speed of the medium and low speed maglev train.

Aim: In order to solve the above problem, and compensate the levitation force reduced by the eddy current effect.

Methods: The FEA method is used to obtain the magnetic field distribution and levitation force changing with the train speed. And taking the middle and low speed maglev trains and rails of Changsha Maglev Express as the research object, we have adopted two solutions, and the prototypes of airsprings and levitation magnets are manufactured and tested in the train.

Results: The test result show that the currents of the windings at the front end of the two forefront electromagnets are reduced obviously.

Conclusion: In this paper, the medium and low speed maglev train and rail used by Changsha Maglev Express are studied, the eddy current effect is analyzed, and two solutions are proposed. The results show that the solution methods can alleviate the eddy current effects to some extent.

Keywords: maglev transportation system, maglev train, eddy current, electromagnet

INTRODUCTION

Compared with traditional urban rail vehicles, medium and low speed maglev trains use electromagnetic force for support and guidance, and they are equipped with linear motors for drive. There is no mechanical contact between the vehicle and the rail, which has high running speed, low noise and strong climbing ability. With its significant advantages such as comfort and maintenance, it is one of the main directions for the development of urban rail vehicles in the future.

To reduce the rail manufacturing cost, the rail of the medium and low speed maglev transportation system generally adopts a solid structure. When the train is

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

running, eddy currents are generated in the rail. The magnetic field generated by the rail eddy current will weaken the electromagnets' levitation force, especially the forefront electromagnet. Because it establishes the magnetic field first in the rail, the magnetic flux at that position changes the most, and the influence of the eddy current effect is also most significant. The test was conducted on the Changsha Maglev Express: the current of the forefront electromagnet was more than 30 % higher than the average value of other electromagnet currents, resulting in serious heating of the forefront electromagnet.

As early as 2004 [1] analyzed and calculated the eddy current effect of maglev transportation systems and gave relationships between levitation forces, eddy currents, air gap magnetic density and velocities. However, literature 1 only gave analysis results and did not propose specific solutions.

In the dissertation of Chinese scientists Zheng Lili, Li Jie, Li Jinhui [2] used the analytical method and the finite element method to analyze the influence of rail eddy currents on the levitation forces of medium and low speed maglev trains and proposed to put the permanent magnets at the front of electromagnets to compensate for the loss of levitation forces. And a pilot study was conducted on the CMS-04 medium and low speed maglev train on the Tangshan test line in China.

However, permanent magnets have permanent magnetism. Therefore, levitation magnets using permanent magnets are prone to adsorb iron foreign materials. If they get stuck between the electromagnets and rail, it will seriously affect the safety of the train. Thence, no permanent magnet is used in the current commercial maglev trains.

To solve the above problems, taking the middle and low speed maglev trains and rails of Changsha Maglev Express as the research object, we have adopted two solutions: the first solution is to reduce the area of the air springs installed above the forefront electromagnets. Thus under the same air pressure, the load of this position can be reduced so that reducing the current of the levitation electromagnets in this position; the second solution is to increase the number of forefront electromagnet's windings and the length of the magnetic pole, thus its levitation capacity will be enhanced, and under the same load conditions, the current will drop.

This article will introduce the analysis and calculation of the above two solutions and experiments for them.

RAIL EDDY CURRENT EFFECT ANALYSIS

Changsha Maglev Express started being in commercial operation on May 6, 2016. At present, there are six trains operating on the line. By the end of June 2018, it has been in safe operation for 1.7 million kilometers and carried nearly 6 million passengers. It is called as version 1.0 commercial maglev train in China.

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.

As shown in Fig. 1, the medium and low speed maglev train of Changsha Maglev Express consists of three carriages. The train has a total length of 48 m, a width of 2.8 m, a maximum operating speed of 100 km/h, and a maximum carrying capacity of 363 passengers.

Fig. 1. Medium and low speed maglev train of Changsha Maglev Express

Fig. 2 shows the data of forefront electromagnet current on version 1.0 maglev train, while the average current of other electromagnets is 28.21 A. As the speed increases, the forefront electromagnet current also increases, which is 1.54 times larger than in the stationary state and is 1.37 times larger than the average current of other electromagnets. The eddy current effect at the forefront electromagnet of the train leading to the decrease of the levitation force. To compensate the loss of levitation force, closed-loop control system will increase the current output automatically.

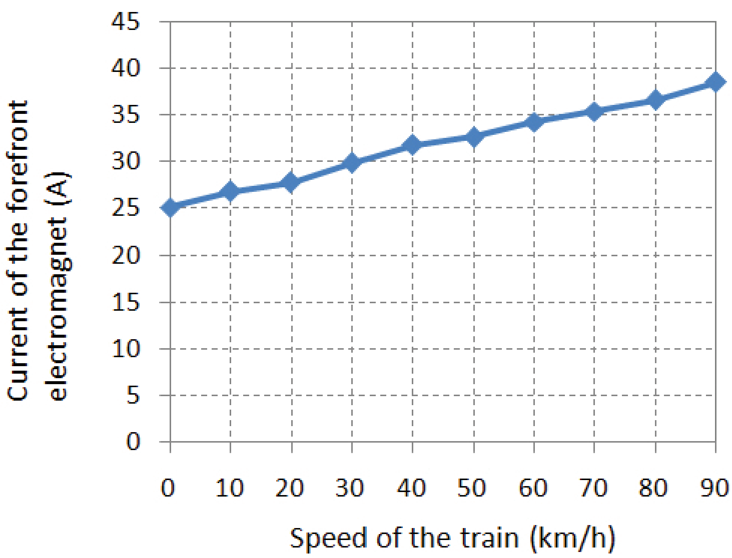


Fig. 2. Data of electromagnet current at different speeds of maglev train

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

doi: 10.17816/transsyst201844129-137

To fulfill the need of transportation between the center of city and the satellite cities, CRRC ZELC has designed and manufactured version 2.0 commercial maglev train with the speed grade of 160 km/h based on version 1.0 commercial maglev train. As the increase of the speed, the eddy current effect at the end of the train increases heavily.

Because the version 2.0 commercial maglev train is still under commissioning, we only get the analysis results of the drop of levitation force when the speed of the train reaches 160 km/h.

The structure of rail and levitation electromagnet in Changsha is shown in Fig. 3. They both made of steel Q235, with the conductivity of 5×10^6 S/m, saturated magnetic density of 1.4 T and the density of 7850 kg/m^3. The B-H curve of steel Q235 is shown in Fig. 4.

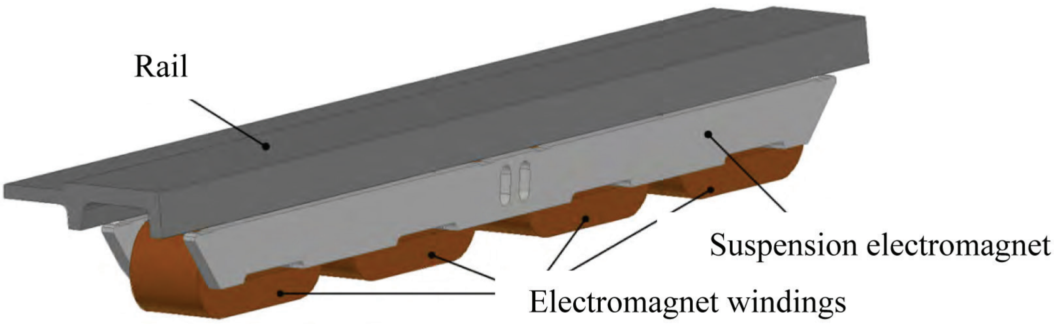


Fig. 3. Structure of rail and levitation electromagnet

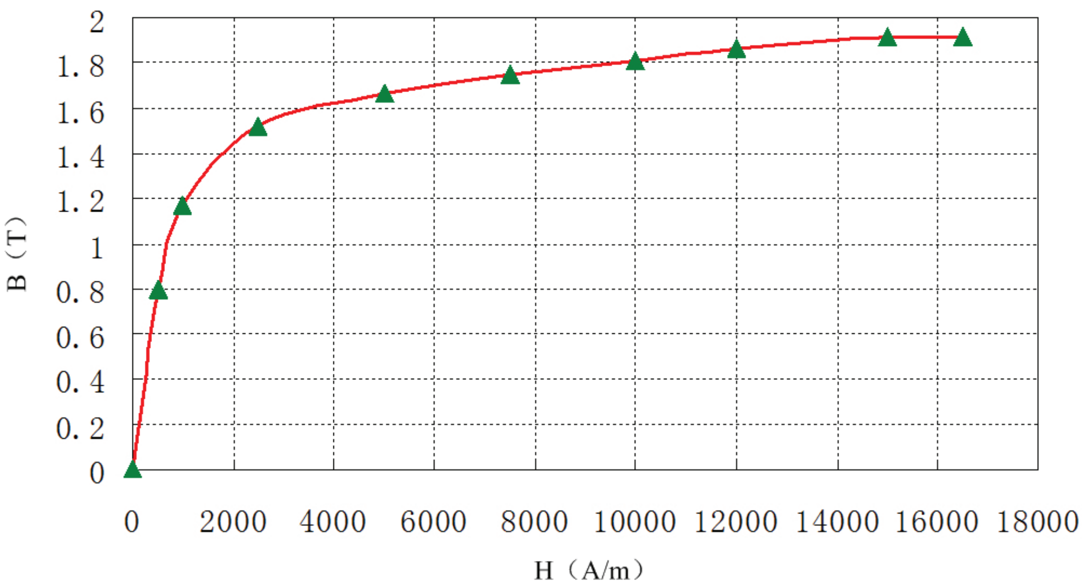


Fig. 4. B-H curve of Q235

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

doi: 10.17816/transsyst201844129-137

Combining the above structure and material properties, we use the three-dimensional electromagnetic field finite element analysis to shows that the levitation force of the forefront electromagnet drops by nearly 40 % at a speed of 160 km/h, as shown in Fig. 5.

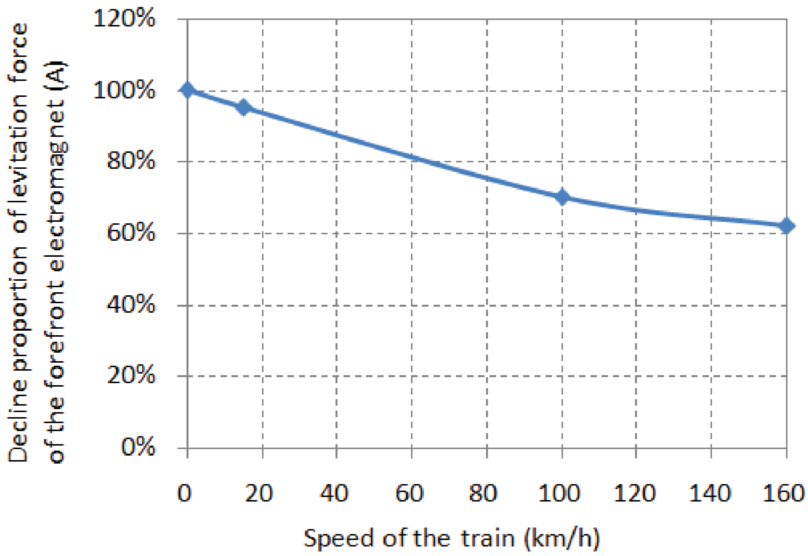


Fig. 5. Relationship between speed and levitation force of forefront electromagnet

FIRST SOLUTION

To solve the problem of current increasing at the forefront electromagnet caused by the decreasing of levitation force, the most straightforward method is to reduce the load on the forefront electromagnet. The train body and passengers' weight are transmitted to the bogies via the air springs and then to the levitation electromagnets. The pressure of the air springs is controlled in groups, and the pressure of the air springs in one group is the same. Therefore, the area of the air springs above the forefront electromagnets can be reduced to cut down the load on the electromagnets.

As is shown in Fig. 6, every carriage has 20 air springs, divided into 4 groups for control. The pressure in one group is the same. For instance, as for the first group, if we adopt "smaller" air springs above the electromagnets, the load can be divided among the electromagnets that correspond to the other four air springs, and the second group is similar.

In the version 1.0 maglev trains, we conducted comparative tests using "standard" air springs and "smaller" air springs, respectively. The experiments' data is shown in Table 1. It can be seen that with a smaller air springs, the load is reduced by an average of about 19 %.

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

doi: 10.17816/transsyst201844129-137

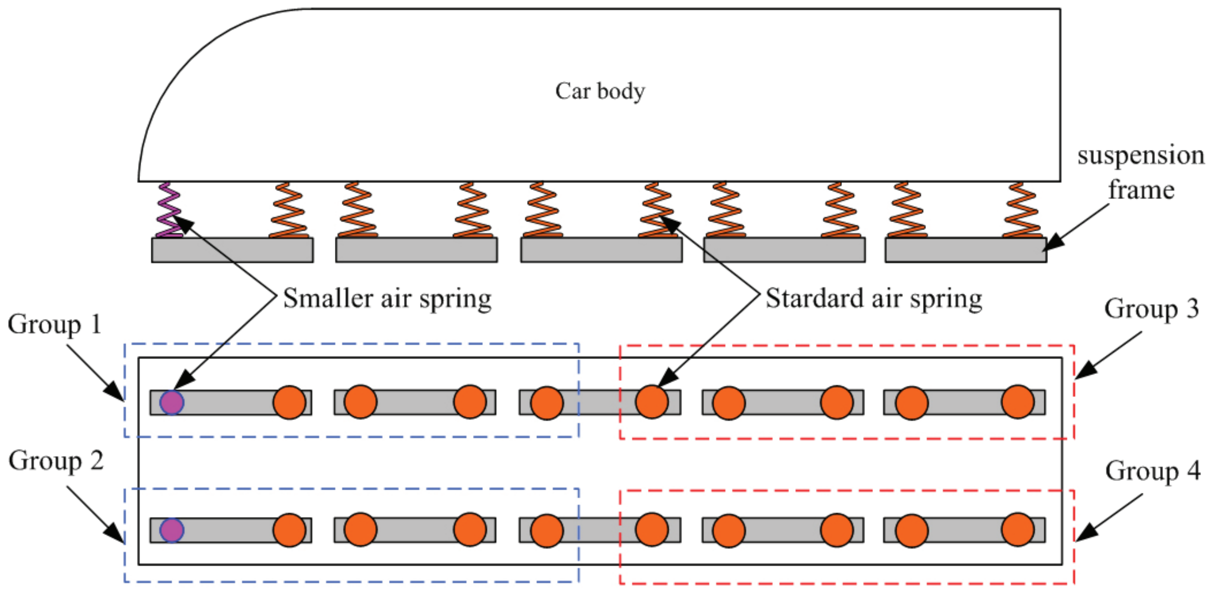


Fig. 6. Arrangement of air springs on the maglev train

Table 1. Load comparative between standard and smaller air springs

Pressure of air spring (MPa)	0.4	0.5	0.6	0.7
Load of standard air spring (kN)	8.5	10.7	13.0	15.3
Load of smaller air spring (kN)	6.9	8.7	10.5	12.2
Percentage of load decreasing (%)	18.8	18.7	19.2	20.3

SECOND SOLUTION

The second solution is to increase the number of windings of the forefront electromagnets and to lengthen the length of the electromagnet cores synchronously. At present, this solution has been adopted on version 2.0 maglev train, but since the version 2.0 maglev train just went off the assembly line on June 13th, 2018 (as shown in Fig. 7), it is still in the commissioning stage, only the data of the train running at low speed is currently available. (As shown in the figure), there is no experimental data when the train is running at a speed of 160 km/h.

As shown in Fig. 8, the standard levitation electromagnet consists of 4 windings divided into two groups. Two windings in each group are connected in series and controlled by one levitation controller. The extended forefront levitation electromagnet consists of 5 windings. The first group at the front end contains 3 windings controlled by one levitation controller. The second group at the back end contains 2 windings, controlled by another levitation controller. As the number of the first set of windings at the front end increases, so the iron core lengthens, a

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

doi: 10.17816/transsyst201844129-137

Fig. 7. Version 2.0 commercial maglev train with speed grade of 160 km/h

larger levitation force can be generated at the side of the three windings at the front end when the same current is passed in, or, under the condition that the load is not changed, the three windings at the front end require smaller current.

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):129-137

doi: 10.17816/transsyst201844129-137

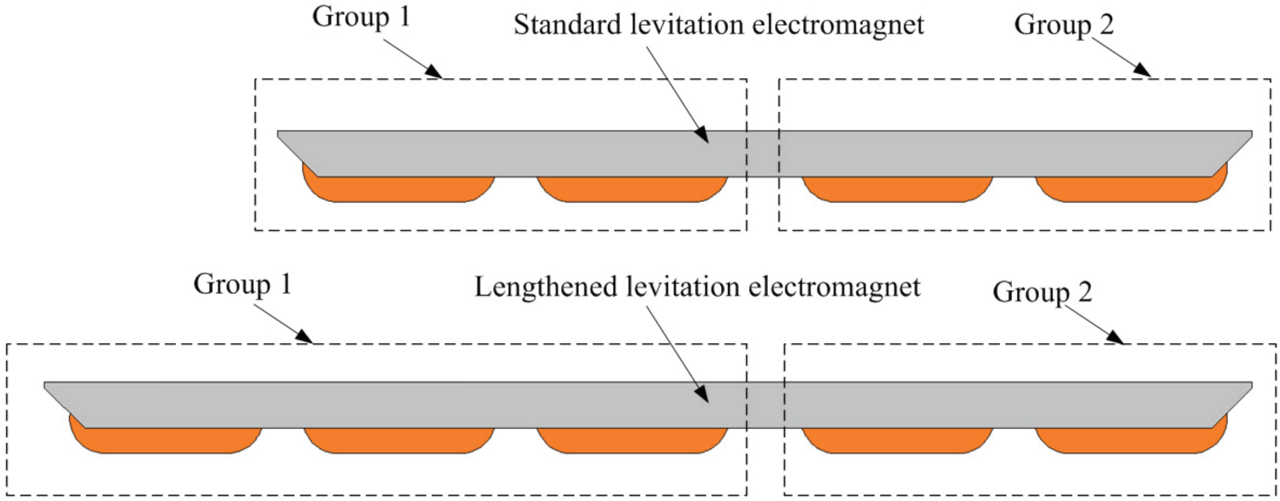


Fig. 8. Comparison of lengthened levitation electromagnets and standard levitation electromagnets

After experiments, the currents of the windings at the front end of the two forefront electromagnets were only 15.12 A and 16.38 A, while the average currents at other positions were 21.84 A. The average current reduces by 31 %.

CONCLUSION

This paper studied on the problem that the rail eddy current will weaken the levitation force of forefront electromagnets of medium and low speed maglev trains, and proposed two specific solutions and conducted experimental testing. The results show that adopting smaller air springs above the forefront electromagnets or increasing the number of the forefront electromagnets' windings and lengthening the iron core can alleviate the eddy current effects to some extent.

ACKNOWLEDGEMENS

This paper is supported by the National Key Research and Development Plan (No. 2016YFB1200601).

References

1. Ohsaki H, Du J. Influence of Eddy Current Induced in Steel Rails on Electromagnetic Force Characteristics of EMS Maglev Systems. Proceedings of the Maglev'2004. 2004;2:960-965.

Received: 20.10.2018. Revised: 16.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844129-137

2. Zheng L, Li Jie, Li J. Research on the Influence of Eddy Current Induced in Steel Rails on the Levitation Force of a Maglev Train [dissertation]. Changsha (Hunan, P.R.C): National University of Defense Technology; 2010.

Information about the authors:
Ying Yang, Master, Professor Level Senior Engineer;
ORCID: 0000-0002-3125-2126;
E-mail: 2560828867@qq.com

Wenyue Zhang, Ph.D, Senior Engineer;
ORCID: 0000-0002-7005-6283;
E-mail: zhang-wen-yue@126.com

Laisheng Tong, Ph.D, Professor Level Senior Engineer;
ORCID: 0000-0001-6905-5198;
E-mail: alanatlsh@126.com

Qibiao Peng, Bachelor, Professor Level Senior Engineer;
ORCID: 0000-0003-0082-4221;
E-mail: pengqibi@sina.com

Huajun Luo, Master, Professor Level Senior Engineer;
ORCID: 0000-0002-8569-5686;
E-mail: 1484904208@qq.com

Jianguo Suo, Bachelor, Professor Level Senior Engineer;
ORCID: 0000-0003-2669-6926;
E-mail: bajiuwangyue@126.com

To cite this article:
Yang Y, Zhang W, Tong L, et al. Analysis and Solution of Eddy Current Induced in Rail for Medium and Low Speed Maglev Transportation System. *Transportation Systems and Technology.* 2018;4(4):129-137. doi: 10.17816/transsyst201844129-137

UDC [УДС] 004.056.5
DOI 10.17816/transsyst201844138-145

© A. A. Kornienko, A. P. Glukhov, S. V. Diasamidze, A. M. Shatov
Emperor Alexander I St. Petersburg State Transport University
(St. Petersburg, Russia)

SOFTWARE PROTECTION OF THE MAGLEV TRANSPORT CONTROL SYSTEM

Background: The article examines the issues of regulation and the development of methodological approaches to ensuring the security of the software system for the management of magnetic-leaving transport at all stages of the life cycle, as well as the development of a tool to detect high-level (logical) software vulnerabilities.

Aim: Development of a methodology for the creation of an error-free and impact-resistant software for the management system of magnetic-levitational transport.

Methods: In the development of the methodology, the existing practices of searching for errors and vulnerabilities in software and approaches to the algorithmization of program code were studied.

Results: During the study, a methodology was developed for creating an error-free and impact-resistant software for the management system of magnetic-levitational transport, which makes it possible to exclude the possibility of errors in the software, which significantly increases the safety of the overall transportation process.

Conclusion: The application of the developed technique will improve the security of software for magnetic levitation transport control system from destructive external influences.

Keywords: magnetic levitation transport, error-free software, information security, algorithmization

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

© А. А. Корниенко, А. П. Глухов, С. В. Диасамидзе, А. М. Шатов
Петербургский государственный университет путей сообщения
Императора Александра I
(Санкт-Петербург, Россия)

ЗАЩИТА ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ СИСТЕМЫ УПРАВЛЕНИЯ МАГНИТОЛЕВИТАЦИОННЫМ ТРАНСПОРТОМ

Обоснование: Рассматриваются вопросы нормативного регулирования и формирования методологических подходов к обеспечению безопасности программного обеспечения системы управления магнитолевитационным транспортом на всех этапах жизненного цикла, а также разработки инструментального средства обнаружения высокоуровневых (логических) уязвимостей программного обеспечения.

Цель: Разработка методологии создания безошибочного и устойчивого к воздействиям программного обеспечения системы управления магнитолевитационным транспортом.

Методы: При разработке методологии были изучены существующие на данный момент практики поиска ошибок и уязвимостей в ПО и подходы к алгоритмизации программного кода.

Результаты: В ходе исследования была разработана методология создания безошибочного и устойчивого к воздействиям программного обеспечения системы управления магнитолевитационным транспортом, которая позволяет с большой вероятность исключить наличие ошибок в ПО, что значительно повышает безопасность перевозочного процесса в целом.

Выводы: Применение разработанной методики позволит повысить уровень защищённости ПО системы управления магнитолевитационным транспортом от деструктивных внешних воздействий.

Ключевые слова: магнитолевитационный транспорт, безошибочное программное обеспечение, информационная безопасность, алгоритмизация

INTRODUCTION

Magnetic levitation transport now is one of the most promising and environmentally friendly modes of transport. Its advantages include low power consumption, low operating costs due to reduced friction between the parts of the rolling stock and the track. In addition, the use of the technology of magnetic levitation allows the rolling stock to reach speeds of about 500–600 km/h, which is comparable with the speed of the aircraft.

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844138-145

The disadvantages of this approach include the high cost of implementation, which is due to the complexity of the technology used, and the inability to use the existing infrastructure for this type of transport.

The most active developments in this direction are carried out by the following countries: Germany; Japan; China; South Korea.

The greatest progress has now been made by China: at the moment the maglev route that runs from Pudong International Airport to the Shanghai Metro station Longyang Road is the only one where commercial operation of high-speed rolling stock on a magnetic cushion is carried out. The maximum speed reached by the train on this track is 430 km/h.

In Russia now a magnetic-levitation transport system is being developed, which will be operated on the Port of Bronka (St. Petersburg) – the station "Vladimirskaya" (Gatchina, Leningrad region). A distinctive feature of this system is its focus on freight traffic. To organize this system will be used many subsystems, one of the most important in which is the control system. The basis of this subsystem is an automated control system for the magnetic levitation transport.

The safety of control systems is one of the main aspects of its functioning, because negative impact on this system can be provided both on critical information resources and on the safety of the transportation process.

At the heart of most of the impacts on these systems is the exploitation of existing vulnerabilities. At the same time, most of them are caused by errors that are present in the software used by these systems.

At the moment, there are many ways that allow you to detect errors and vulnerabilities in program code. But their significant drawback is that they are often unable to detect such types of medium – and high-level vulnerabilities, such as errors in the logic of program execution. Search for these vulnerabilities is currently poorly developed and requires the presence of highly qualified information security experts.

CONTROL SYSTEM OF MAGNETIC LEVITATION TRANSPORT AS AN OBJECT OF INFORMATION SECURITY

Control System of magnetic levitation transport is one of the key parts of the magnetic-levitation transport system, as a result of which strict requirements are imposed on it for correct and safe operation, including the requirements for protecting critical information circulating in it and information security in general.

When considering this system as an information security object, it is necessary to determine what information resources are available in the system. To

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844138-145

do this, it is necessary to allocate the information infrastructure and information that should be protected, as well as determine the level of significance of the protected information.

The creation and use of error-free and destructive software, which is used at various hierarchical levels of the system, occupies an important place in ensuring the safety of automated control systems by the movement of magnetic-levitational transport. In conjunction with the observed increase every year in the number of detected vulnerabilities, the task of their search in the software is critical from the point of view of information security.

The existing set of software vulnerabilities can be conditionally divided according to their location in the code:

− low-level vulnerabilities (data access errors, errors in calculations, etc.);

− medium-level vulnerabilities (errors in the logic of the software);

− high-level vulnerabilities (errors in the software architecture).

At the moment, most of the ways to find vulnerabilities in the software are not satisfactory, because they are aimed at finding only low-level vulnerabilities and can not always provide full coverage of the code and functionality of the investigational product. Therefore, it is proposed to develop a methodology for creating error-free and impact-resistant software for the control system of magnetic levitation transport.

METODOLOGY FOR CREATING ERROR-FREE AND IMPACT-RESISTANT SOFTWARE FOR THE CONTROL SYSTEM OF MAGNETIC LEVITATION TRANSPORT

The proposed methodology is aimed at finding errors and vulnerabilities in the control system software and includes three main steps:

− creation of built-in control mechanisms in microprocessor devices as elements of the system of functional control and diagnosis;

− verification and testing;

− confirmation of conformity of software, which can be used at all stages of its life cycle.

According to these directions, the model of the investigated subject area was drawn up, presented in Fig. 1 and containing the areas of vulnerability life in different representations of the software.

Based on this model, an algorithm was developed for creating error-free and impact-resistant software for the system, as shown in Fig. 2.

As the source data, you must use the machine or source code of the software under investigation, which will be converted at the first stage of the algorithm

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):138-145

doi: 10.17816/transsyst201844138-145

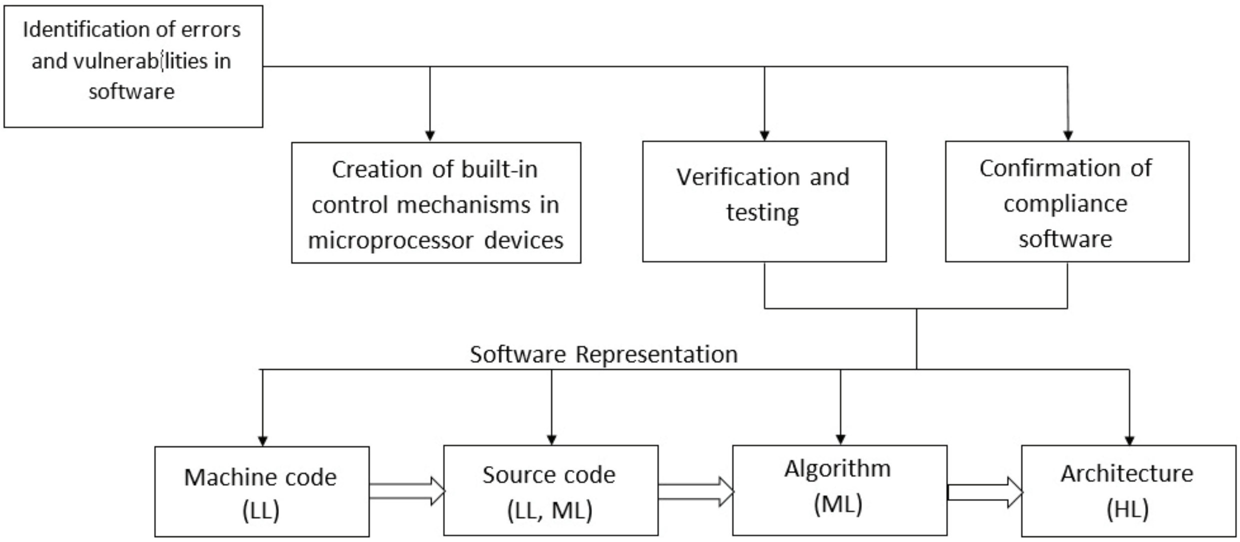


Fig. 1. Model of subject area

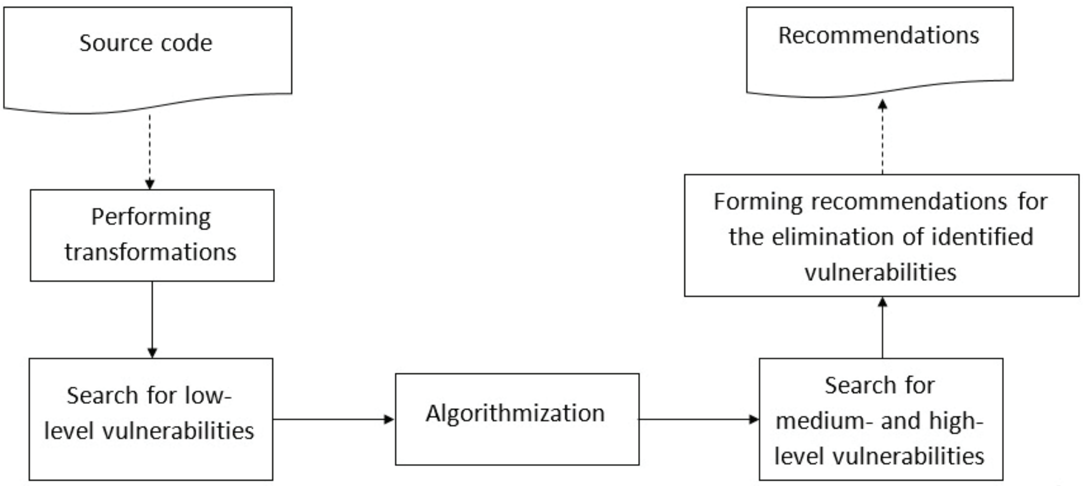


Fig. 2. Algorithm for creating error-free and impact-resistant software

(as a rule, they will consist in removing comments from program texts and other redundant syntactic constructions).

The next step is to look for low-level vulnerabilities in the resulting code using existing methods at the moment. To ensure a higher percentage of coverage, several methods can be shared. Next, the code is algorithmized using the DRAKON language – a visual algorithmic programming language and modeling that provides greater visibility [3, 7]. The rules for creating diagrams in the DRAKON language were created with an emphasis on the requirements of ergonomics, so they were initially optimized for the perception of algorithms by a person mainly using computer graphics.

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

Transportation Systems and Technology. 2018;4(4):138-145
doi: 10.17816/transsyst201844138-145

The schemes developed with the help of the specified language are simple and understandable even to a person far from programming, which will allow to expand the circle of specialists who can use the developed methodology. This is due to the fact that the DRAKON focuses on the visual component, which greatly improves the readability of the program. In its usual form, block diagrams allow you to graphically display the logic of the program, but with a sufficiently large amount of code, they become cumbersome and lose visibility. Schemes in the DRAKON language, in turn, allow us to depict the solution of complex problems in an extremely clear and clear form. This is achieved by using special rules of ergonomic algorithms: for example, the intersection of algorithm lines is forbidden in them, which usually complicates its understanding by the user.

Unlike the classical block diagrams, the exit to the left of the condition is forbidden in the dragon-scheme, and routes are drawn according to the principle “the right is the worse”, i.e. the more to the right of the algorithm is a block, the more unpleasant situation it describes. This makes it easier to understand the finished schema. Another advantage of dragon schemes is that at the moment they cover most of the popular and most commonly used high-level programming language. Thus, the scheme obtained at the third stage of the algorithm will make it possible to obtain a visual representation of the investigational software.

At the fourth stage, both medium- and high-level vulnerabilities are searched. At the same time, this stage can be conducted either manually by an expert in information security, or automated. To automate the work at this stage, it is necessary to develop specialized programs that allow analyzing block diagrams and identifying critical locations in them.

At the last stage of the methodology, in accordance with previously identified vulnerabilities, recommendations are made for their elimination. After making the necessary changes to the program code, it is necessary to re-pass through the stages of the algorithm in order to make sure that there are no previously detected and those that appeared after fixing the vulnerabilities.

CONCLUSION

The currently available methods for finding errors and vulnerabilities in software are usually aimed at finding low-level vulnerabilities and can not always provide full coverage of the code and functionality of the product under investigation. The proposed methodology will allow the creation of software that is likely not to contain any errors and vulnerabilities, which is critical when using such software in traffic control systems.

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844138-145

Библиографический список / References

1. Корниенко А.А., Диасамидзе С.В. Подтверждение соответствия и сертификация программного обеспечения по требованиям безопасности информации: учеб. пособие. – СПб.: ПГУПС, 2009. [Kornienko AA, Diasamidze SV. Confirmation of compliance and certification of software for information security requirements: schoolbook. St. Petersburg; 2009. (In Russ.)].
2. Диасамидзе С.В. Метод выявления недекларированных возможностей программ с использованием структурированных метрик сложности: дис.…канд. техн. наук. – СПб; 2012. [Diasamidze SV. Metod vyavleniya nedeklarirovannikh vozmozhnostey program s ispolzovaniem structurirovannikh metrik slozhnosti [dissertation]. St. Petersburg; 2012. (In Russ.)].
3. Израилов К.Е. Метод алгоритмизации машинного кода для поиска уязвимостей в телекоммуникационных устройствах: дис.…канд. техн. наук. – СПб; 2017. [Izrailov KE. Method algoritmizatcii mashinnogo koda dlya poiska uyazvimostey v telekommunikatcionnykh ustroistvakh [dissertation]. St. Petersburg; 2017. (In Russ.)].
4. Академия Microsoft. Лекция 8: Методы проверки и тестирования программ и систем. Доступно по: https://www.intuit.ru/studies/courses/2190/237/lecture/6130. Ссылка активна на 10.03.2018. [Akademiya Microsoft. Lekciya 8: Metody proverki i testirovaniya programm i sistem. Available from: https://www.intuit.ru/studies/courses/2190/237/lecture/6130]. (In Russ.) Accessed 10 March 2018].
5. Академия Microsoft. Лекция 12: Проверка требований. Доступно по: https://www.intuit.ru/studies/courses/2190/237/lecture/6138. Ссылка активна на 15.03.2018. [Akademiya Misrosoft. Lekciya 12: Proverka trebovanij. Available from: https://www.intuit.ru/studies/courses/2190/237/lecture/6138. (In Russ.) Accessed 15 March 2018.].
8. Кулямин В.В. Методы верификации программного обеспечения. – М.: Институт системного программирования им. В.П. Иванникова РАН, 2008. [Kuliamin VV. Metody verifikacii programmnogo obespecheniya. Moscow: Ivannikov Institute for System Programming of the RAS; 2008 (In Russ.)].
7. ДРАКОН. Доступно по: https://ru.wikipedia.org/ДРАКОН. Ссылка активна на 17.03.2018. [DRAKON. Available from: https://ru.wikipedia.org/DRAKON. (In Russ.) Accessed 17 March 2018].

Information about the authors:
Anatoly A. Kornienko, Dr., prof.;
eLibrary SPIN: 8943-3184; ORCID: 0000-0002-6076-7241;
E-mail: kaa.pgups@yandex.ru

Alexander P. Glukhov, Dr.;
eLibrary SPIN: 6034-3986; ORCID: 0000-0001-5368-4109;
E-mail: inib@pgups.ru

Svetlana V. Diasamidze, PhD, docent;
eLibrary SPIN: 1207-0600; ORCID: 0000-0003-2683-0697;
E-mail: sv.diass99@yandex.ru

Received: 01.11.2018. Revised: 26.11.2018. Accepted: 17.12.2018.

Alexander M. Shatov;
E-mail: alexsandr.shatov@yandex.ru

Сведения об авторах:
Анатолий Адамович Корниенко, д-р техн. наук, профессор;
eLibrary SPIN: 8943-3184; ORCID: 0000-0002-6076-7241;
E-mail: kaa.pgups@yandex.ru

Александр Петрович Глухов, д-р техн. наук;
eLibrary SPIN: 6034-3986; ORCID: 0000-0001-5368-4109;
E-mail: inib@pgups.ru

Светлана Владимировна Диасамидзе, канд. техн. наук, доцент;
eLibrary SPIN: 1207-0600; ORCID: 0000-0003-2683-0697;
E-mail: sv.diass99@yandex.ru

Александр Михайлович Шатов;
E-mail: alexsandr.shatov@yandex.ru

To cite this article:
Kornienko AA, Glukhov AP, Diasamidze SV, Shatov AM. Software Protection of the Maglev Transport Control System. *Transportation Systems and Technology.* 2018;4(4):138-145. doi: 10.17816/transsyst201844138-145

Цитировать:
Корниенко А.А., Глухов А.П., Диасамидзе С.В., Шатов А.М. Защита программного обеспечения системы управления магнитолевитационным транспортом // Транспортные системы и технологии. – 2018. – Т. 4. – № 4. – С. 138–145. doi: 10.17816/10.17816/transsyst201844138-145

DOI 10.17816/transsyst201844146-156

© G. Q. Wang[1], S. T. Hu[1], G. F. Zeng[1], F. Ye[1], W. L. Xu[2]
[1] Tongji University
(Shanghai, China)
[2] CCCC Tunnel Engineering Company Limited
(Beijing, China)

GRAY RELATIONAL ANALYSIS BETWEEN THE MAGLEV-STRUCTURAL DEFORMATION AND CONSTRUCTION PARAMETERS OF THE SHIELD TUNNEL CROSSING THE SHANGHAI MAGLEV PROTECTED AREA

Background: Shanghai Maglev Demonstration Line is the only commercial high-speed maglev train line in the world, which has multiple functions such as transportation, exhibition, tourism and sightseeing. Besides, Shanghai Maglev Demonstration Line has been in operation for 15 years, and has been operating safely and punctually. Maglev protected area are located within 30 meters of the left and right sides of the Shanghai Maglev Demonstration Line and unrelated persons are not allowed to enter the area. When there were external construction invading the protected area, it is neccessary to do the comprehensive technical monitoring and protection. Without similar project to refer to, Metro Line 13 traversing Shanghai Maglev Line was a big challenge. Therefore, effective measures should be taken to do the comprehensive technical monitoring. Finding the relation between the maglev deformation and shield construction parameters was an important part of the monitoring.

Aim: This thesis aimed at finding the relation between the maglev deformation and shield construction parameters and controlling the maglev deformation in the crossing of Metro Line 13, thus guiding the shield construction.

Methods: This thesis calculated the gray relation between the maglev deformation and shield construction parameters from the cause of deformation of the maglev by the gray relation analysis.

Results: The construction parameters optimization and the sensitivity control are carried out. Meanwhile, combined with the measured results of deformation monitoring, the multi means parallel monitoring data are analyzed synthetically and the data are checked, and the construction parameters are adjusted reasonably to make the pier column deformation in the controllable permissible range, having ensured the safe operation of the maglev.

Conclusion: The calculation results has provided a reference for realizing active control on the influence of shield construction on the maglev and has remedied the defect that could only use deformation monitoring but could not control the deformation actively in the past work. The gray relational analysis has a certain effect on controlling the influence of shield construction on surrounding structures and has certain reference significance for subsequent similar projects.

Keywords: High-speed Maglev, Protection Zone, Comprehensive Technical Monitoring and Protection, Deformation Monitoring, Settlement, Gray Relation, Shield Construction Parameters

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.

PROJECT PROFILE AND THE PROPOSAL OF THE PROBLEMS

There were three lines traversing the maglev between pier 182 to pier 185 respectively of metro line 13, up line, down line and approaching line, the plan shown in Fig. 1. The maximum diameter was 6 760 mm and the maximum burial depth was 18.65 m of the shield of which the third tunnel was a curve of 250 m radius, shown in Fig. 2. The construction face of the project was rather close to the maglev pile, leading to troublesome and risky construction. Deep soil in the vicinity of the shield would produce varying degrees of deformation in the course of shield tunneling, thus leading to the deformation of the maglev pile, cushion cap and column. The project metro line 13 traversing the maglev was a new challenge in the history of engineering technology. Meanwhile, the deformation were effectively controlled and the safe operation of the maglev was guaranteed through comprehensive technical monitoring and protection.

The construction sequence of the three tunnels was the upline, the downline and the approaching line. The upline and the downline being basically orthogonal to the maglev line, the construction of the two lines were relatively simple. For the construction of the third small radius curve, the relationship between the maglev deformation and the shield construction parameters within the scope of the project could be found in the course of the construction of the first two tunnels to guide

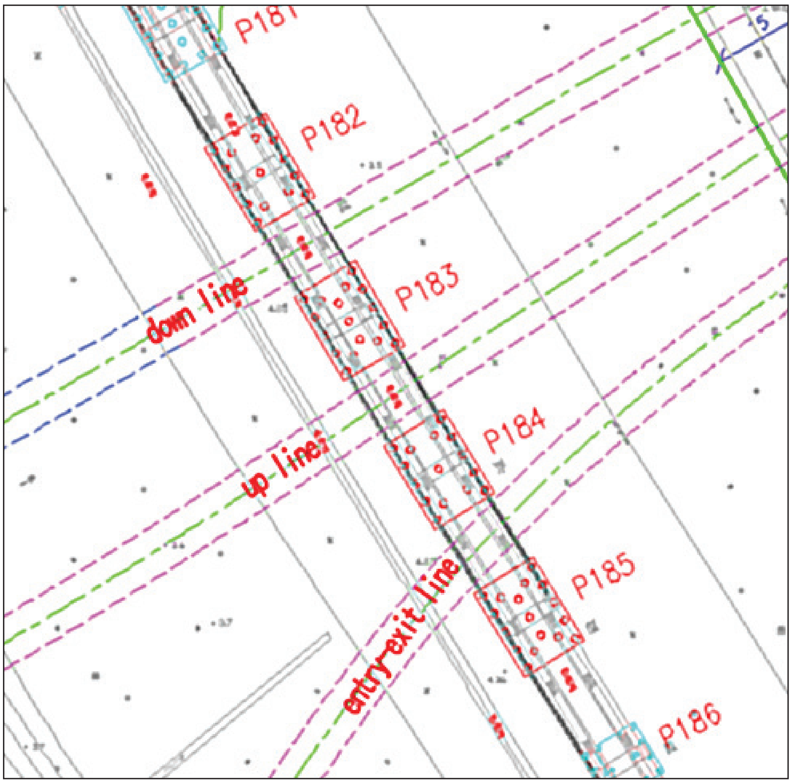


Fig. 1. Metro line13 traversing the maglev plane

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

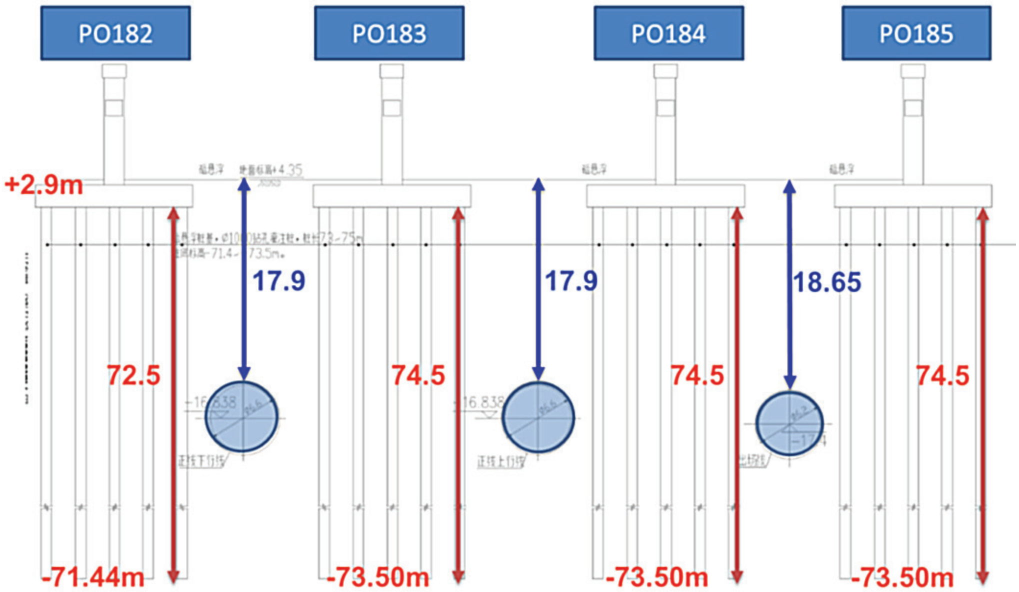


Fig. 2. The relationship between the maglev structure and the shield tunnel

the construction of the third tunnel. It was found in the project that the key to solve the problems was to study the gray correlation degree between varying construction parameters and the deformation of different reference points. On the bases of studying the deformation regularity between the construction parameters and the maglev structures of the first two tunnels, this thesis has calculated the gray correlation degree between the maglev deformation and the shield tunnel parameters during the third tunnel construction by setting simulative segment and then obtains the sensitivity sequence of the construction parameters to guide the optimization and adjustment of the construction parameters. The deformation of the surface and the maglev pile are well controlled.

DEFORMATION REQUIREMENTS OF THE MAGLEV STRUCTURES AND MONITORING POINTS LAYOUT

1. Deformation control value

According to the "Administrative Measures for Maglev Safety Protection Zone of Shanghai Maglev Transportation Development", combined with the relevant technical requirements of the maglev system, controlling value requirements of additional deformation produced from external engineering were shown as follows:

1). Total foundation settlement did not exceed 2 mm (accounting for 10 % of the total design settlement);

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

2). The cumulative uneven settlement of the front and rear support pier was not more than 1mm;

3). The cumulative lateral (y-direction) offset of the front and rear support pier was not more than 1mm;

4). The cumulative uneven settlement of the left and right support pier of the same cap was not more than 0.5 mm.

2. Monitoring range and monitoring requirements.

1). Monitoring range.

The deformation monitoring was carried out for the piles and cable trenches in the range of the P0181 to P0186 maglev piles which were badly affected by the construction.

2). Monitoring points layout and monitoring requirements:

− Monitor the vertical deformation of the A and B rail piers in the above range and the tilting deformation of the A, B rails crosswise bridge and along to the bridge, and calculate the y-direction offset corresponding to the function element for the tilt;

− Monitor the vertical deformation of the strong and weak cable trenches in the above ranges.

− Monitor Ground subsidence;

− Monitor Deep soil deformation.

The monitoring points layout shown above can accurately reflect the characteristics of the maglev deformation. The deformation value are reference sequence in the calculation of gray correlation degree in this paper of which monitoring accuracy badly affects the effectiveness of the calculation results. Therefore, it is needed to use high precision measurements to monitor the deformation.

GRAY CORRELATION DEGREE ANALYSIS

Gray system theory produces a concept that analyzes various elements by using gray correlation degree analysis, intending to find out the numerical relationship among all factors in a system. Thus, gray correlation degree analysis has provided a quantitative measure for the development of a system and is very suitable for dynamic process analysis. Gray system theory has been widely used in economy, science and technology, agriculture, industry, ecology and so on since the founding by professor Deng in 1982. Besides, the theory has been well applied in the field of engineering in the past ten years.

1. Deng's correlation degree.

For the elements between two systems, the dimension of relevance that changes with time or different objects is called gray correlation degree. In the

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

system, if the trend of two elements is consistent, that is, the degree of synchronous change is relatively high, it is said that the degree of correlation between the two factors is relatively high, otherwise, it is relatively low. After the dimensionless treatment, the correlation coefficient of the comparison sequence for the reference sequence is calculated as follows:

$$\zeta_i(k) = \frac{\min_i \min_k \left|x_0(k) - x_i(k)\right| + \rho.\max_i \max_k \left|x_0(k) - x_i(k)\right|}{\left|x_0(k) - x_i(k)\right| + \rho.\max_i \max_k \left|x_0(k) - x_i(k)\right|}, \qquad (1)$$

where K=1, 2, …, m; j=1,2,…n; $x_0^{(k)}$ is reference sequence, $x_j^{(k)}$ is comparison sequence, time dimension is n.

Gray correlation degree of comparison factor for reference factor is calculated as follows:

$$r_{oi} = \frac{1}{n}\sum_{k=1}^{n}\zeta(k) \qquad (2)$$

2. General method for calculating gray correlation degree:

The general steps for calculating gray correlation degree are shown as follows:

1). Determining reference sequences and comparison sequences

The sequences that reflect the behavior characteristics of the system are reference sequence. The sequences that affect the factor composition of behavior of the system are comparative sequences.

2). Dimensionless processing of data

Owing to the fact that the physical meaning of each factor in the system are different, the dimensions of the data are not necessarily the same. Therefore, it is not convenient to compare the factors, that is, it is difficult to obtain correct conclusions. So the dimensionless processing is usually carried out when doing the gray correlation analysis.

3). Calculating correlation coefficient

The correlation coefficient between comparison sequence and reference sequence is calculated and the correlation coefficient matrix is formed according to the formula (1).

4). Calculating gray correlation degree

For each factor in comparison sequences, the average value of correlation coefficients on time dimension is the gray correlation degree between the factor and the reference factor. In turn, the gray correlation degree matrix can be obtained.

5). Sorting of gray correlation degree

For one reference sequence, different evaluation indexes are sorted according to the gray correlation degree, thus the affecting factors being obtained.

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.

doi: 10.17816/transsyst201844146-156

There are many methods to do dimensionless processing, such as the initial value method, the mean value method, the range method and so on. The application range of each method is different. Because of the irregular settlement of the pier column, the mean value method is mainly used in this paper. At the same time, the initial value method and the absolute gray correlation degree are used to check.

CALCULATION OF THE GRAY CORRELATION DEGREE BETWEEN THE CONSTRUCTION PARAMETERS AND THE DEFORMATION

1. Shield construction parameters.

During the shield construction, it is necessary to control dozens of parameters mainly including the propulsion speed, the soil pressure and the quantity of grouting which are obtained by the sensors arranged in the shield. The influences of the deformation produced by these parameters in different geological conditions and different engineering conditions are different, which requires us to start from the cause of the deformation of the maglev pier columns to study the relationship between the parameters of the shield construction and the deformation of the shield, and to get the sort of its sensitivity, so as to optimize and adjust the most sensitive parameters, and then control the deformation value in the allowable range.

The data from December 1 to 11, 2017 were calculated every two days. The value of 14 main construction parameters and time dimensions are shown in Table 1.

Table 1. Construction Parameters / Comparison Sequence and Time Dimension Values

Date / **Construction Parameters**	**12.01**	**12.03**	**12.05**	**12.07**	**12.09**	**12.11**
Soil pressure in the soil warehouse (right) X1 (KPa)	231.375	225.546	208.848	206.689	212.531	213.264
Soil pressure in the soil warehouse (left) X2 (KPa)	243.958	239.286	232.469	218.796	230.747	23.820
Soil pressure in the soil warehouse (down) X3 (KPa)	283.583	283.950	280.082	267.157	277.054	281.381
Total thrust X4 (KN)	13 407.41	13 530.76	12 909.65	12 533.29	12 993.91	13 446.64
'A' flow rate accumulated value X5 (L)	1449.61	1468.13	1437.65	1369.96	1343.21	1443.27

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

Date / Construction Parameters	12.01	12.03	12.05	12.07	12.09	12.11
Jack average speed X6 (mm/min)	10.4292	10.2941	10.4856	9.9900	10.2614	10.7950
Grouting accumulated (A) X7 (m^3)	1,56477	1.55962	1.50714	1.38591	1.55736	1.54042
Cutter torque X8 (KN-m)	1161.90	1099.34	1038.19	1065.33	1084.29	1004.74
Push pressure X9 (KPa)	14041.7	13637.0	13356.4	13157.5	14046.5	13951.0
Up Push pressure X10 (KPa)	11977.9	12931.5	9197.9	10318.1	12301,7	10546.0
Right Push pressure X11 (KPa)	9705.0	8624.8	8012.4	6243.5	6789.6	8489.1
Left Push pressure X12 (KPa)	8648.8	12556.7	11455.1	9577.6	9885.1	9469.0
Down Push pressure X13 (KPa)	12853.3	8807.1	11200.4	12064.5	11170.1	12923.4
Spiral pressureX14 (KPa)	5239.2	4951.3	4905.8	4914.7	4944.4	4805.0

2. Maglev structure facility deformation values

For the same time period, the deformation values of the maglev facilities and the surface points are shown in Table 2.

Table 2. Pier Columns and Surface Points / Reference Sequences and Time Dimension Values

Total settlement (mm) / Monitoring points	12.01	12.03	12.05	12.07	12.09	12.11
P0182A	1.32	1.12	1.15	1.16	1.59	1.36
P0182B	1.66	1.32	1.53	1.48	1.78	1.63
P0183A	0.93	0.84	0.96	0.89	0.96	1.06
P0183B	0.98	0.87	1.11	0.92	0.87	1.11
P0184A	1.06	1.03	1.27	1.00	1.16	1.49
P0184B	1.27	1.13	1.23	0.93	1.14	1.37
X01	–1.22	–1.31	–0.73	–1.36	–1.20	
X03	2.37	1.87	0.91	–0.81	–3.52	
DB08	0.53	0.12	–0.49	–1.92	–4.84	

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

3. Gray correlation degree calculation between construction parameters and deformation values

According to Deng's gray correlation degree calculation method, the correlation degrees were calculated based on the values listed in Table 1 and Table 2. Gray correlation degree matrix (part) is shown in Table 3 (ρ is 0.485).

Table 3.Gray Correlation Degree Between Construction Parameters and Deformation Values

Correlation Degree / Monitoring points	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10	r11	r12	r13	r14
P0182A	0.67	0.71	0.70	0.71	0.69	0.71	0.75	0.64	0.73	0.68	0.59	0.53	0.63	0.66
P0182B	0.77	0.79	0.76	0.79	0.74	0.77	0.77	0.73	0.80	0.71	0.61	0.57	0.72	0.76
P0183A	0.72	0.77	0.80	0.78	0.77	0.83	0.78	0.70	0.80	0.60	0.59	0.61	0.72	0.73
P0183B	0.64	0.68	0.69	0.69	0.71	0.73	0.66	0.59	0.68	0.54	0.58	0.64	0.65	0.63
P0184A	0.60	0.64	0.65	0.63	0.61	0.66	0.63	0.58	0.61	0.50	0.53	0.63	0.59	0.61
P0184B	0.66	0.67	0.65	0.64	0.66	0.68	0.64	0.64	0.63	0.52	0.64	0.53	0.66	0.67

SENSITIVITY ANALYSIS AND COMPREHENSIVE EVALUATION

The correlation degree matrix of the 9 reference sequences (pier column and surface deformation value) and 14 comparison sequences (shield construction parameters) is synthetically analyzed, and the conclusions are drawn as follows:

1. Comprehensive analyze the gray correlation degree matrix between the settlement value of P0182-P0184 A, B rail pier, cable ditch points, surface points and the above construction parameters, it's order is summarized as follows:

For the pier column: ranked in the top 6 parameters are $r_6 > r_9 > r_2 > r_3 > r_4 > r_7$, and ranked in the last 4 are $r_8 > r_{11} > r_{12} > r_{10}$.

For the surface points: ranked in the top 6 parameters are $r_{13} > r_{10} > r_8 > r_{14} > r_9 > r_6$, and ranked in the last 4 are $r_5 > r_7 > r_{12} > r_{11}$.

2. The order of above gray correlation degree shows that the sensitivity of the construction parameters for the piers and the ground points is different. For example, the most sensitive parameters for the piers are jack average speed and propulsion pressure, while the most sensitive parameters for the surface points are propulsion pressure (up) and propulsion pressure (down). Therefore, the settlement deformation can be effectively controlled by controlling the high-impact construction parameters.

3. When calculating the gray correlation degree of the strong cable trenches monitoring points, the order of the sensitivity of the construction parameters is

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

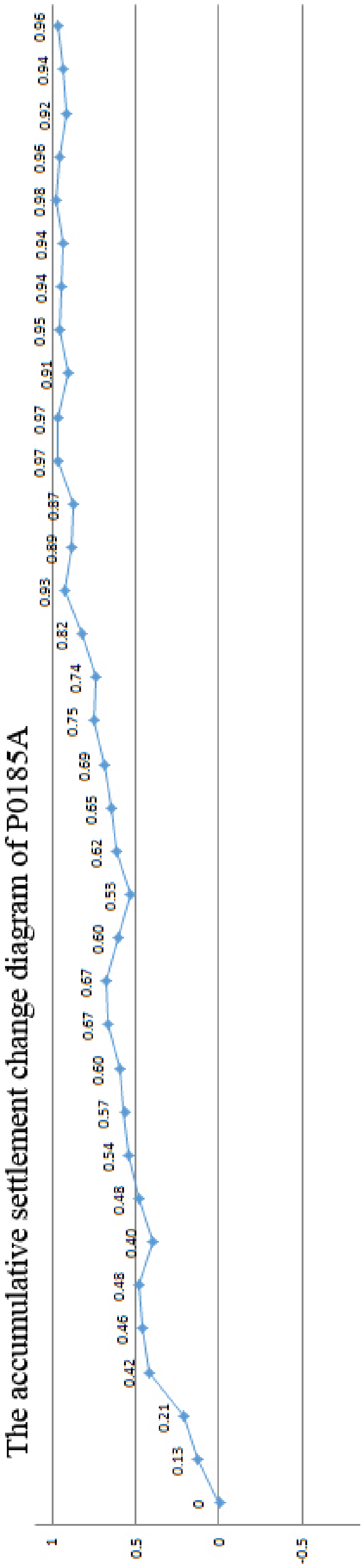


Fig. 3. Deformation curve of P0185A

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.
Transportation Systems and Technology. 2018;4(4):146-156

doi: 10.17816/transsyst201844146-156

consistent with that of the piers, which may be because the strong cable trenches are located on the maglev load bearing platform, leading to their structural stability the same as that of the piers.

4. Owning to the fact that the deformation of the piers may be floating up, for the data which has both positive data and negative data, it's necessary to pretreat the data to be consistent so that the results will be closer to the actual calculation.

5. The relationship between the above construction parameters and the monitoring data is not universally applicable and only applies to the foundation of the above project. In general, for new projects, it is capable to select the appropriate test sections for simulation calculations to obtain optimal construction parameters and methods.

6. According to the above correlation degree sequencing results, the construction parameters optimization and the sensitivity control are carried out. Meanwhile, combined with the measured results of deformation monitoring, the multi means parallel monitoring data are analyzed synthetically and the data are checked, and the construction parameters are adjusted reasonably to make the pier column deformation in the controllable permissible range, having ensured the safe operation of the maglev. Among them, the deformation curve of P0185A is shown in Fig. 3. The adjustment and optimization of construction parameters can control the deformation of pier columns in the allowable range according to the order of correlation.

CONCLUSIONS

Through the calculation and analysis of the correlation degree between the pier column and the ground point settlement value of the construction parameters of the 13 shield of Shanghai subway, the most sensitive shield construction parameters are adjusted according to the degree of correlation degree, and the deformation of the shield construction to the magnetic floating structure is effectively controlled, ensuring the safe operation of the Shanghai Maglev Line. Practice has proved that, it is applicable to use Deng 's correlation degree calculation method to calculating the correlation degree of the construction parameters used in the shield-through-maglev engineering, which is a great reference for future similar projects.

ACKNOWLEDGEMENTS

This work is supported by the National Key Technology R&D Program of the 13th Five-year Plan, Research on Key Technologies of Medium Speed Maglev Transportation System (2016YFB1200601).

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.

References

1. Deng JL. Gray System Theory Tutorial. *Huazhong University of Science and Technology Press*. China. 1989.
2. Wu XM. Maglev Train. *Shanghai Science and Technology Press*. China.
3. Administrative Measures for Maglev Safety Protection Zone of Shanghai Maglev Transportation Development. *Shanghai Maglev Inc*. China. 2009.
4. Wang GQ, Hu ST, Ye F, Zeng GF, LV Q. Comprehensive Technical Monitoring for Maglev Structure during the Metro Shield Tunnel Undercrossing the Shanghai Maglev Protected Area. Proceedings of 18th COTA International Conference of Transportation Professionals. China. Beijing; 2018.
5. Wang GQ, Bi S, Zeng GF, Ye F. Analysis of the influence of external construction on maglev protection area. Proceedings of the 23th International Maglev Conference. Germany. Berlin. 2016;2:67-73.
6. Yu XD, Sun QL. Application of grey system theory in construction control of continuous girder bridge. *East China Highway*. 2008(5):22-23.

Information about the authors:
Wang Guo-Qiang, Doctor, Associate Researcher;
ORCID: 0000-0001-8880-6110;
E-mail: wgq_135246@163.com

Hu Song-Tao, Bachelor;
ORCID: 0000-0003-2057-1022;
E-mail: husongtao95@126.com

Zeng Guo-Feng, Doctor, Associate Researcher;
ORCID: 0000-0001-6818-9178;
E-mail: zengguofeng@tongji.edu.cn

Ye Feng, Doctor, Associate Researcher;
ORCID: 0000-0001-8278-2170;
E-mail: yefeng@tongji.edu.cn

Xu Wen-Li;
ORCID: 0000-0001-9017-2436;
E-mail: xumenli002@163.com

To cite this article:
Wang GQ, Hu ST, Zeng GF, et al. Gray Relational Analysis Between the Maglev-Structural Deformation and Construction Parameters of the Shield Tunnel Crossing the Shanghai Maglev Protected Area. *Transportation Systems and Technology.* 2018;4(4):146-156. doi: 10.17816/transsyst201844146-156.

Received: 31.10.2018. Revised: 25.11.2018. Accepted: 17.12.2018.